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Photograph by Craig Cutler

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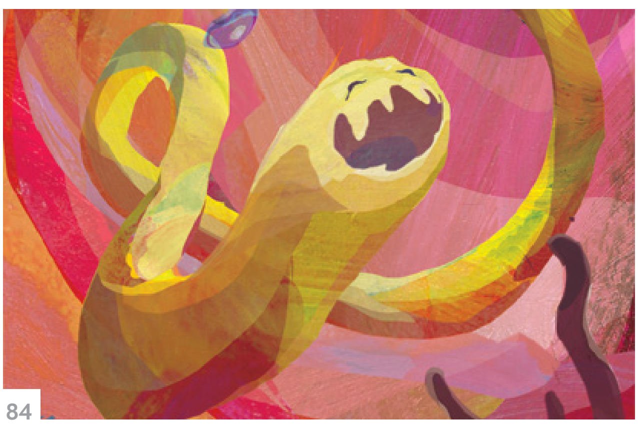
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Laura Helmuth is editor in chief of *Scientific American*.
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Our Human Side

The Thwaites Ice Shelf is one of the most important geological features on the planet, and it's in trouble. The 800-square-kilometer slab of ice floats in front of Antarctica's enormous Thwaites Glacier and braces it in place. In the past few years scientists have found new ways the ice shelf is melting, cracking and wobbling. Science journalist Douglas Fox accompanied researchers as they pulled sleds full of radar equipment across the ice to study its interior, finding surprises with every new observation. The consequences of a Thwaites Ice Shelf collapse would be catastrophic, flooding coastal towns around the world, and it could start to crumble in a decade.

The implications of Thwaites research are grim, but the article about it, starting on page 32, is actually a lot of fun. The details make the story: Antarctic ice that crunches like cornflakes, the snowy *fuff* when scientists detonated explosives, and the possibility that on a future mission, scientists will wake up to find themselves unexpectedly floating on an iceberg.

The editors at *Scientific American* encourage our authors to share the amusing, weird, awe-inspiring, scary, *human* side of science in their stories. Paleoanthropologist Jeremy DeSilva really came through for us on page 72, with a memorable anecdote about researchers playing dodgeball with elephant dung before they discovered an important bed of fossilized footprints. I laughed out loud when I read his methodology for a research project that involved applesauce (I won't spoil it). The fascinating conclusion to all this Very Serious Research is that humans learned to walk many times in our evolutionary history, with very different gaits and postures. When multiple hominin species lived in the same place, they might have been able to tell one another apart from a distance based on how they walked.

New techniques for assessing brain activity are revealing that some patients who appear to be in a coma or unresponsive can understand some of what's happening around them. Detecting "covert consciousness" can help guide treatments and predict clinical outcomes. Neurologists Jan Claassen and Brian L. Edlow are working to improve methods of testing for covert consciousness, and on page 60, they explore what it means for our understanding of consciousness itself.

Subatomic particles appear to be breaking a rule called "lepton flavor universality." Physicists are getting really excited about their strange behavior, and I hope you will, too, after you read theoretical physicist Andreas Crivellin's story on page 66. The Standard Model has been extremely successful at helping us understand the subatomic world, but it doesn't explain everything. Strangely behaving particles have the potential to reveal what's wrong or what's missing from our understanding of everything from neutrinos to dark matter.

Certain newly invented materials behave strangely as well. Some of these "metamaterials" bend light in unusual ways, cloaking an object to make it invisible. They're engineered at the nanoscale, with a range of features that bend light and sound to their whim. Physicist and engineer Andrea Alù describes on page 42 how metamaterials can support superconductivity and break symmetries.

Citizens' assemblies are groups of people who work together to understand a problem, find solutions and build consensus, especially for divisive issues. They've been around since ancient Greece, but they're becoming more popular lately. These assemblies are much more inclusive and representative than representative democracy, but the process of choosing participants can still be tricky. Computer scientist Ariel Procaccia on page 52 shares his work on creating and refining an algorithm for democracy. SA

Illustration by Nick Higgins

July 2022

"Too often human impact on the environment is reduced to a 'mea culpa' description."

JENNIFER HAHN *TURIN, ITALY*

VOYAGERS BY THE NUMBERS

I very much enjoyed "Voyagers to the Stars," Tim Folger's article on the history and the status of the Voyager spacecraft. But I was puzzled when he mentioned that Voyager 1 and 2 will continue their journey and pass the nearest neighboring star, Proxima Centauri, in 16,700 and 20,300 years, respectively.

NASA's website says that the Voyagers won't reach the halfway point to Proxima Centauri for 40,000 years and will travel two light-years to do so. If I use the speeds given at NASA's Voyager mission status web page and assume 365.25 days in a year, I get approximately 70,000 years for Voyager 1 and 78,000 years for Voyager 2 to travel four light-years.

JOHN CARY *Sacramento, Calif.*

The graphic in the box "The Longest Voyage" shows both Voyager spacecraft making abrupt course deviations from the plane of the solar system. What was the cause of these course changes? Were they the result of programmed flight changes or some aspect of leaving the solar system?

F. TRACY SCHONROCK *via e-mail*

FOLGER REPLIES: To answer Cary: In 40,000 years the Voyagers will reach the outer edge of the Oort cloud, which is indeed about halfway to Proxima Centauri. But tens of thousands of years before that time, Voyager 1 and 2 will make their closest encounter with that star, coming within about 3.5 and 2.9 light-years of it, respectively. That's not very close: the sun is currently about 4.2 light-years away from Proxima Centauri. On a cosmic scale, the sun and the Voyager spacecraft are essentially the same distance from our nearest stellar neighbor. But because the spacecraft are moving away from the sun, and Proxima Centauri is moving toward it, the Voyagers' closest approach to our neighboring star will occur in 16,700 and 20,300 years.

Regarding Schonrock's question: Voyager 1's trajectory was designed to take it as close as possible to Saturn's moon Titan. That trajectory eventually took Voyager 1 "north" and out of the ecliptic—the plane of the solar system. Voyager 2's path was designed to take it beyond Saturn, to Uranus and Neptune. That path sent Voyager 2 "south" of the ecliptic. These weren't course corrections. Rather the spacecraft were just following the paths that would give scientists the best views of the outer planets.

PAYING FOR THE CLIMATE EMERGENCY

In "Climate Miseducation," Katie Worth reports on the shockingly disproportionate influence that the fossil-fuel industry has in setting science education standards in Texas, which consequently influence much of the textbook content throughout the U.S. As a science educator and school sustainability leader at an international school in Italy, I found the process in Texas of setting standards based on volunteer committees and decision-making by members of the State Board of Education extremely worrying. But I do not entirely disagree with their push to include a "cost-benefit analysis" of energy resources. While there is little doubt this is an attempt to divert attention from the need for climate action, I also see an opportunity.

Too often human impact on the environment is reduced to a "mea culpa" description, with little analysis of decision-making mechanisms that often have led to even further devastation of the environment. Students must acknowledge and demonstrate an understanding of how and why environmentally poor decisions are made to realistically and authentically offer alternatives. By allowing them to analyze the costs and benefits associated with fossil-fuel usage—and who pays—they will certainly come to the same conclusion as any other rational scientist: Although the start-up costs are great, converting our society to renewable energy will save us from the dramatically greater health, social, economic and environmental costs associated with continuing on the current path. And no, it won't be a perfect solution.

JENNIFER HAHN *Turin, Italy*

THE SINGING DETECTIVE

Adam Fishbein's fascinating article "How Birds Hear Birdsong" [May] made me wonder about some issues that I encounter in my own research on popular music singing. It was no surprise to me that the "melodies" birds sing are more of a vehicle for what they are actually communicating through sonic "fine structure." I found the article was based on a very Western way to think about language and music by focusing on abstractions rather than actual sounds. But in Fishbein's defense, this is widely the case in the field.

First, the idea of limiting the conception of music to mere notes (what I call "abstract parameters"), which has been shared by many "traditional" musicologists and music theorists, is now being strongly questioned. Indeed, recent research suggests that popular music listeners, while of course sensitive to pitches (melody), also especially react to aspects of sound production related to timbre. In popular music singing, paralanguage (the surrounding sounds we emit when speaking that are often wrongly considered mere noises) is used systematically to convey rather specific emotional content. Melodies, though essential, act as vehicles to such paralinguistic production.

What about tonal languages such as Mandarin Chinese, for example? Studies


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show that Chinese speakers have a much better ability to identify pitch by ear, or "perfect pitch." While most people recognize a given melody when it is sung in a different pitch despite its new key, there is a large proportion of the population that can hear the shift. For many musicians, each tonality culturally conveys its own emotional signature.

In the research conducted by my colleagues and me—as well as by many other musicologists around the globe—we study microvariations in timbre that are very similar to the fine structures described in the article using the very same tools (waveforms and spectrograms). Many researchers are interested in such finer structures in music precisely because humans are very sensitive to microvariations in timbre (perhaps even more than they are to melodic structures), as well as to those in rhythm. In fact, we came to realize that the lack of study on humans' ability to precisely perceive these finer structures was based on millennial-long Western ideology favoring the abstract over the concrete.

I believe that topics such as birdsong would be a perfect terrain for true interdisciplinary research. We, as musicologists of microvariations, are absolutely ready to contribute (well, at least, I am!).

Serge Lacasse *Full Professor of musicology, Laval University, Quebec*

FISHBEIN REPLIES: Lacasse makes excellent points about the importance of microvariations in music and language. I wholeheartedly agree that this topic is a ripe terrain for interdisciplinary research. Birdsong studies often attempt to draw parallels to syntax and other more abstract parameters of language and music, but I think humans and birds are more similar when it comes to extracting emotional content from subtle changes in sounds. Still, it is the case that songbirds, at least the species studied so far, do appear to be much better than humans at hearing changes in fine structure. This may be because of fundamental anatomical differences in the structure of the inner ear. And although melodic structures in music differ across cultures, the ability to hear melody is universal in humans. Songbirds simply appear to not hear strings of sounds as melodies like we do.

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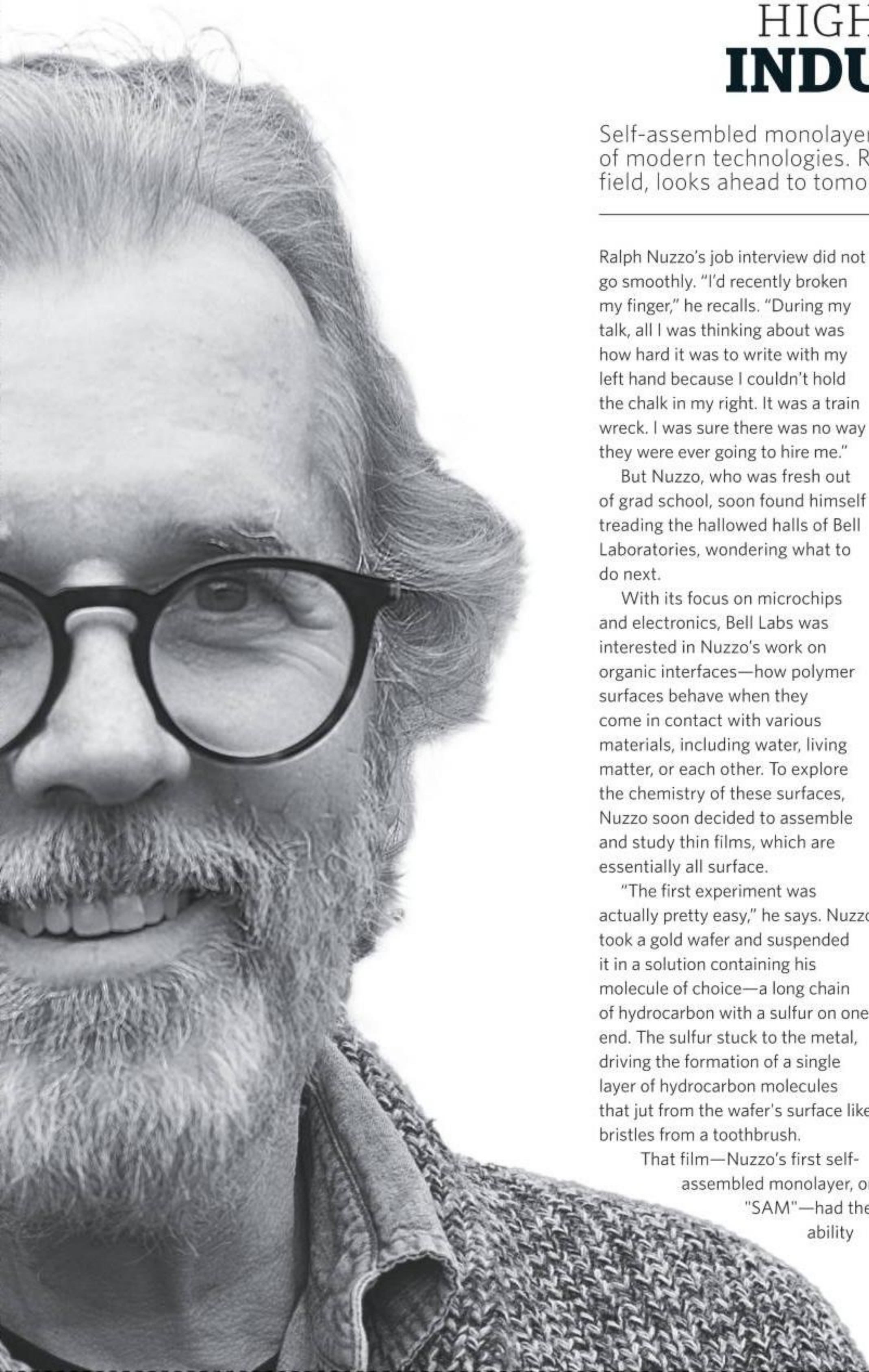


THE CUSTOM COATINGS THAT TRANSFORMED HIGH-TECH **INDUSTRY**

Self-assembled monolayers enable a remarkable array of modern technologies. Ralph Nuzzo, a pioneer in the field, looks ahead to tomorrow's revolutionary materials.

Ralph Nuzzo's job interview did not go smoothly. "I'd recently broken my finger," he recalls. "During my talk, all I was thinking about was how hard it was to write with my left hand because I couldn't hold the chalk in my right. It was a train wreck. I was sure there was no way they were ever going to hire me."

But Nuzzo, who was fresh out of grad school, soon found himself treading the hallowed halls of Bell Laboratories, wondering what to do next.

With its focus on microchips and electronics, Bell Labs was interested in Nuzzo's work on organic interfaces—how polymer surfaces behave when they come in contact with various materials, including water, living matter, or each other. To explore the chemistry of these surfaces, Nuzzo soon decided to assemble and study thin films, which are essentially all surface.

"The first experiment was actually pretty easy," he says. Nuzzo took a gold wafer and suspended it in a solution containing his molecule of choice—a long chain of hydrocarbon with a sulfur on one end. The sulfur stuck to the metal, driving the formation of a single layer of hydrocarbon molecules that jut from the wafer's surface like bristles from a toothbrush.

That film—Nuzzo's first self-assembled monolayer, or "SAM"—had the ability to reject wetting. "I would dip it in a solvent and it would come out completely dry," he says. That physical property suggested there was "something cool going on," says Nuzzo. "But understanding what was happening microscopically was a deeply challenging analytical question." Nuzzo wanted to know how tightly the bristle-like molecules were packed, and in which orientation, as well as how the molecules changed shape and shifted in space as conditions changed.

Enter David Allara, an expert on analytics and all manner of spectroscopic techniques. "Dave had the vision, skills, and quantitative capabilities to make characterization of SAMs doable," Nuzzo says. Together, Nuzzo, Allara, George Whitesides, and Jacob Sagiv share the 2022 Kavli Prize in Nanoscience for the development and characterization of self-assembled monolayers with an amazing array of properties.

"What we learned from SAMs about complex interfacial dynamics and surface-related phenomena was foundational," says Nuzzo. SAMs laid the groundwork for the production of polymer coatings that are used in everything from electronics and semiconductors to medical diagnostics and implantable devices.

Here, Nuzzo describes how today's nanoscience could spawn quantum electronics, nanostructures that interact with living systems, and four-dimensional structures that evolve over time.

What innovations will drive the next generation of electronics?

For decades, transistors have been assembled on thin wafers. This strategy was transformational, but we're at the limits of what can be done in 2D. So the world is starting to lift semiconductors into three-dimensional topologies. Another approach that's receiving intense interest is quantum IT, where you can code more bits per unit real estate because things operate not on charge alone, but on charge and spin. Also deeply interesting is integration using photons rather than electrons.

I can't imagine today's electronics being supplanted by anything less than a highly integrated, high-performance structure of almost unimaginable complexity.

Can we design nanostructures that interact with living matter?

The frontiers of nanoscience are in applications related to medicine. There's a huge distance to traverse before we can approach the interfacial complexity of biological systems. Developing materials that interact with living matter in medically relevant ways is a vibrant area of study.

For example, toward the end of my time at the University of Illinois, my collaborators and I started making scaffolds that can support cells and allow them to survive and maintain their phenotype in 3D microcultures. We took explants from the dorsal root ganglion, which has five different cell types, and fabricated 3D scaffolds that allow these cells to reorganize into structures that mimic those in the peripheral nervous system. Those experiments were enormously complex and hard to do. But things like that point toward approaches for doing nerve repair. If I had another career to invest in, I think I might focus less on semiconductors and a lot more on interacting with living systems.

What are the potential benefits and challenges of engineering systems that change over time?

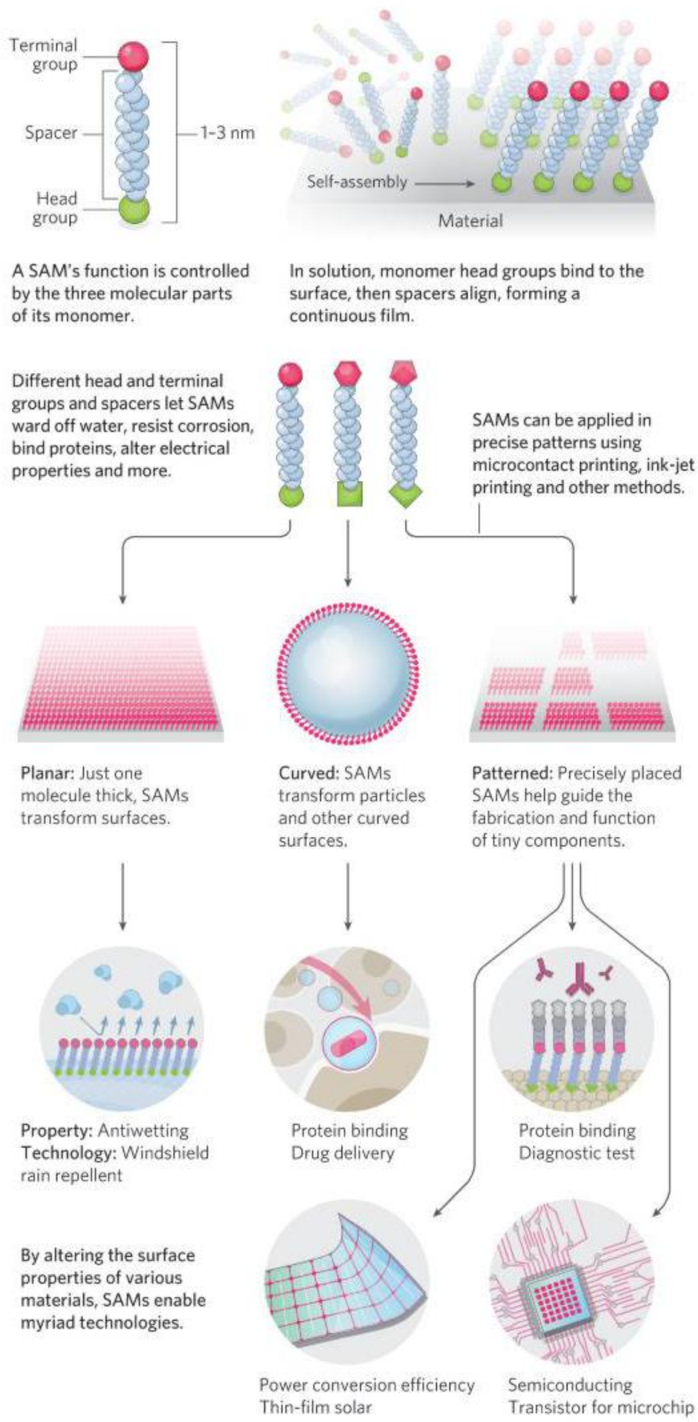
Four-dimensional printing is where you design systems whose form and structure can morph. This is a new frontier. People are making sophisticated structures that fold, origami-like, in response to changes in osmotic forces, and they're using them to make things like actuators that operate like an artificial muscle. Part of what's necessary are materials that change their form and function in response to things they sense, feel and encounter in their environment.

I also like the idea of transient structures or functions, such as an adhesive property that lasts for a certain period and then goes away—like a soft material used for tissue repair or implantable devices that perform their function and then disappear. People like John Rogers, who is a Mozart in this area of engineering, have explored making things as enormously complex as an absorbable pacemaker, which does its work for 30 days and then goes away. We already have absorbable sutures. So we just need to extrapolate that approach to a level of sophistication maybe 15,000 orders of magnitude greater.

To learn more about the work of Kavli Prize laureates, visit kavliprize.org.

THIN FILMS FOR ADVANCED TECHNOLOGY

Coatings called self-assembled monolayers (SAMs) alter a material's physical and chemical properties.



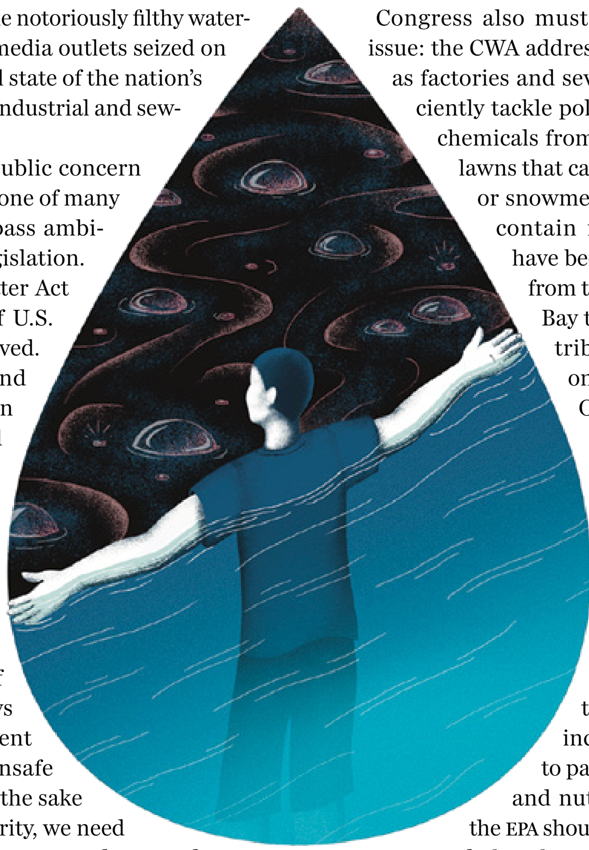
THE KAVLI PRIZE

50 More Years of Clean Water

As the landmark Clean Water Act is challenged in court, our rivers and streams need all the help they can get

By the Editors

When a blaze ignited Ohio's Cuyahoga River on June 22, 1969, it wasn't the first—or worst—time the notoriously filthy waterway had caught fire. But national media outlets seized on it as a stark example of the abysmal state of the nation's waters after decades of unchecked industrial and sewage pollution.



Coming at a time of growing public concern over the environment, the fire was one of many issues that spurred Congress to pass ambitious and bipartisan landmark legislation. In the 50 years since the Clean Water Act (CWA) became law, the health of U.S. rivers, lakes and streams has improved. On the Cuyahoga, insects, fish and birds that are sensitive to pollution have returned, as have kayakers and recreational fishers.

But the CWA is under attack in the court system by people who would weaken it, and there are multiple sources of pollution that the current law doesn't adequately address. The National Resources Defense Council reports that as of 2019, more than 80 percent of bays and estuaries and around 55 percent of rivers and streams harbored unsafe levels of at least one pollutant. For the sake of our health and economic prosperity, we need stronger protections for our waterways—and we need our courts to uphold the CWA against its current challenges.

A major question in the court debate is what bodies of water the CWA covers. The objective of the law "is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and to eliminate the "discharge of pollutants into the navigable waters." The Environmental Protection Agency and the Army Corps of Engineers, which administer the CWA, have always interpreted those mandates broadly. But the Trump administration issued rules in 2020 that left out many wetlands and smaller streams under the reasoning that they were not navigable and therefore were not subject to pollution limits.

Although the Biden administration has proposed rules that would restore protections to small streams and wetlands, a Supreme Court case on the docket for this fall could undermine them. In *Sackett v. EPA,* the petitioners argue that wetlands on their property—and by extension millions of acres of other wetlands—are not covered by the law. But these wetlands connect with other, navigable waters, and as 12 scientific societies have stated in an amicus brief, that argument "rejects hydrological reality." Water in a river cannot be adequately protected unless we also protect the many sources that feed into it. The Supreme Court therefore must follow the science and rule in favor of the EPA. This ongoing legal wrangling also underscores the need for Congress to strengthen the CWA using the best available science.

Congress also must finally confront a long-standing issue: the CWA addresses point sources of pollution, such as factories and sewage systems, but it does not sufficiently tackle pollution from nonpoint sources—the chemicals from parking lots, roadways, fields and lawns that can be washed into waterways by rain or snowmelt. Agricultural and lawn fertilizers contain nitrogen and phosphorus, which have been shown to feed toxic algal blooms from the Gulf of Mexico to the Chesapeake Bay to Lake Erie. Such blooms have contributed to fish die-offs, and in 2014 one rendered the tap water in Toledo, Ohio, unsafe to drink.

Congress must take stronger action to rein in this pollution, whether by amending the CWA beyond a largely voluntary measure exempting agricultural runoff or through other legislation that targets nonpoint sources. Policy makers should work with farmers, ranchers and scientists to develop strategies tied to clear metrics and provide tangible incentives. One example is a program to pay ranchers in Florida to retain water and nutrients on their lands. In addition, the EPA should set environmental limits for nitrogen and phosphorus so states will have to set standards for them under the CWA, which will help reduce loads of these pollutants from point sources.

We have made notable progress toward Congress's 1972 goal of eliminating pollution from the nation's waters so people can once again fish and swim in them and draw their drinking water from them. The Supreme Court and members of Congress now have the chance to uphold existing law and enact bold, visionary legislation—to live up to the legacy of their predecessors and ensure clean water for the generations to come. SA

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Illustration by Elaine Knox

Richard A. Grucza of the Washington University School of Medicine in St. Louis specializes in addiction treatment and policy relating to alcohol, tobacco and cannabis. **Andrew D. Plunk** of Eastern Virginia Medical School studies how drug policy affects marginalized communities.

Decriminalize Marijuana

Good federal policy could reduce arrests and support a regulated marketplace

By Richard A. Grucza and Andrew D. Plunk

Public opinion has swung rapidly in favor of marijuana legalization, and there is growing discontent among the public and policy makers with the criminalization of low-level drug offenses. As public health researchers who have studied marijuana, alcohol and tobacco policies, we strongly favor decriminalization but are cautious about legalization. Decriminalization and legalization are separate policies relating to the removal of criminal penalties for use and the establishment of legal markets, respectively. Criminalization of marijuana harms people, but the history of legal alcohol and tobacco shows that public health suffers when profits take priority over the public good. Ideal cannabis policies must take into account just and equitable criminal policy, individual liberty and strong regulation.

Our research has shown that decriminalization and legalization can have different outcomes. For decades possession of a small amount of marijuana could lead to large fines and jail time, and many in our field have long thought these penalties are disproportionate to the crime.

In 2009 Massachusetts began reducing penalties such that possession of a small amount of marijuana was akin to a traffic violation. Many states followed. This is decriminalization: fewer or no penalties but not necessarily with laws or infrastructure supporting legal sales. People of color are much more likely to be arrested for possession than white people, and this disparity has worsened in states that have not decriminalized or legalized cannabis.

Yet legalization doesn't completely solve the criminalization problem because people can still break the law through underage possession, illegal sales and other violations. Our research has shown that in states that legalized marijuana and implemented age-restricted commercial cannabis markets, there was no immediate reduction in arrests of people under the age of 21. But in states that decriminalized cannabis possession without fully legalizing it, there were reductions in arrest rates of minors and in enforcement disparities. This may be because states that focused primarily on creating legal markets paid less attention to the details of decriminalization policy, whereas states where decriminalization was the main goal designed legislation for maximal impact on criminal consequences for people of all ages.

Even in states that restrict cannabis use only through civil penalties and fines, poor people and minorities bear the brunt of these consequences. States should remove all penalties for carrying small amounts of cannabis, essentially legalizing possession for personal use but not sales or distribution. We also think states should expunge the criminal records of people who were convicted of possession of small amounts of marijuana and even of low-level sales.

Our current drug policy for marijuana makes little sense. Cannabis rarely ever kills anyone, unlike alcohol and other drugs. And deaths from the latter two are rising. We think the individual choice and freedom stemming from a more liberal cannabis policy could contribute to the common good. Research from Uruguay, Canada and the U.S. suggests that age-restricted legalization of marijuana sales does not lead to large increases in cannabis use among youth, a primary concern of prohibition advocates.

Sound legislation must consider the harms associated with heavy cannabis use, however. Cannabis is an addictive substance. As with alcohol and other drugs, a small percentage of users consume most of the cannabis produced. Cannabis acutely affects learning and memory and therefore overall functioning and productivity. Over time these effects can worsen work and educational outcomes, which in turn impact health and life expectancy. Thus, laissez-faire legalization with few regulations is harmful. History offers multiple examples of societal harm from lax regulation, including of the tobacco, alcohol and pharmaceutical markets.

We urge policy makers to alleviate the suffering caused by unnecessary and ineffective criminal penalties for marijuana violations. They must limit the power and influence of the industry through taxes, restrictions on advertising and promotion, and a purchase age of 21. Decades of research show that such actions can reduce the harms associated with addictive substances. Failure to take them will result in a new addiction industry in the U.S. SA

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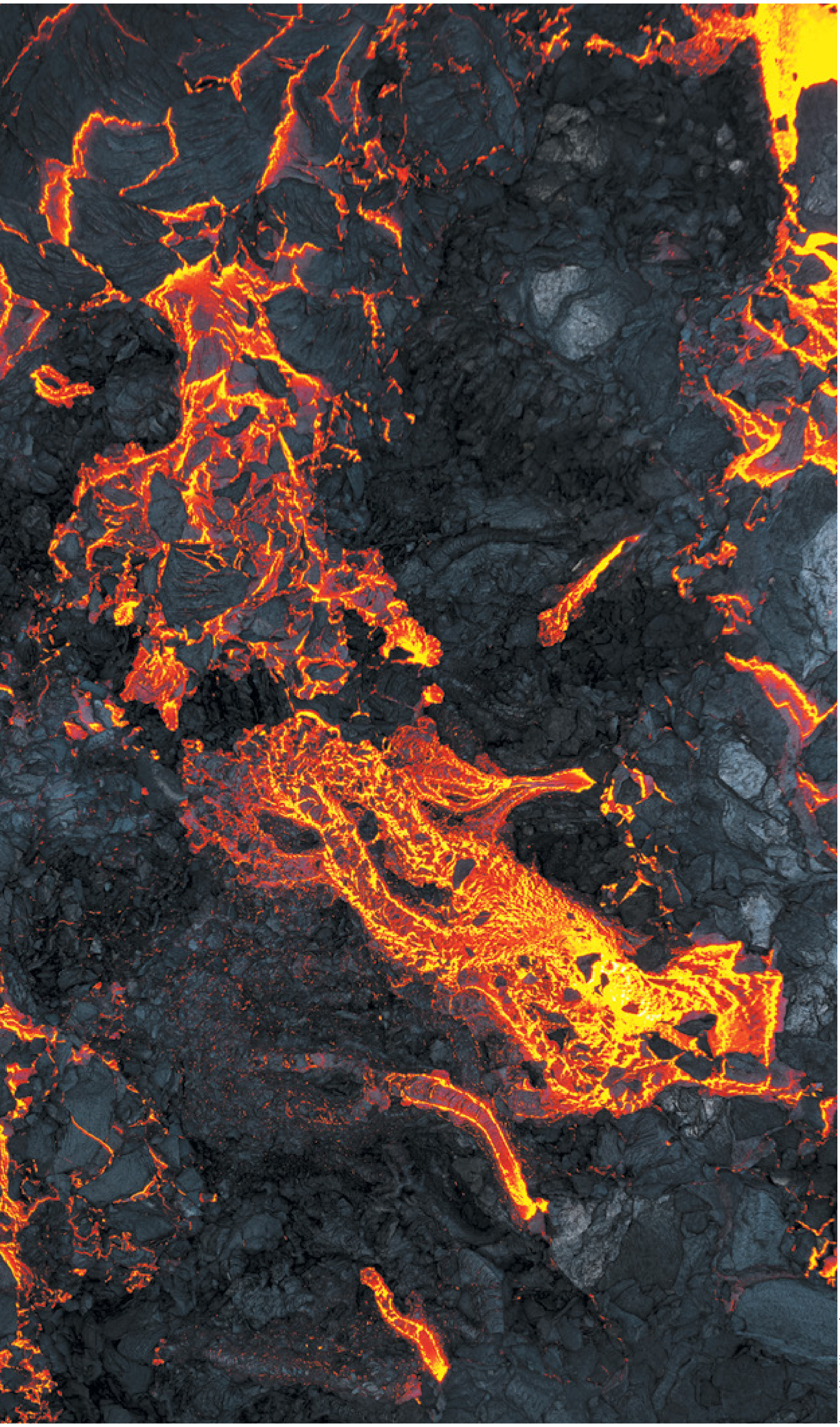
Illustration by Chloe Zola

ADVANCES

Observers are visible opposite lava during Fagradalsfjall's 2022 eruption.



Jeroen Van Nieuwenhove

INSIDE

- Density drives myriad forms of cannibalism in animals
- COVID-19 infections between mammals are tracked in new database
- Rotting fish unlock secrets of fossilization
- Water activates a sustainable paper-based battery

GEOLOGY

Volcanic Awakening

Iceland's sudden eruptions hint at the end of an 800-year lull

Breaking more than seven months of calm, western Iceland's Reykjanes Peninsula once again burst into volcanic flames this past summer. After a swarm of localized earthquakes in late July and early August, the Fagradalsfjall volcano spewed a flood of lava into the Meradalir valleys—close to the barely cooled lava from the same volcano's 2021 eruption—treating tourists and researchers to the vibrant red-orange glow of fresh molten rock just 20 miles from the capital city of Reykjavik.

Such striking volcanic displays are not uncommon in Iceland, one of the world's geologically youngest landmasses. The whole country is the product of millions of years of eruptions and is perfectly placed for ongoing volcanic activity—and scientists say the recent series of eruptions may signal the reawakening of a powerful volcanic system after 800 years.

The summer eruption gave researchers a valuable chance to collect data on the developing system and subterranean magma movement. Measurements at this uniquely accessible site will also help scientists better predict when and why volcanic eruptions occur, says geophysicist Sigrun Hreinsdóttir: "We don't have a lot of [view-obscuring] vegetation in Iceland, so we are getting a wealth of satellite imagery that really helps us understand what's going on. The entire image is quite astonishing for one of these events."

Iceland straddles the boundary between two of Earth's tectonic plates, enormous crust fragments that fit together like puzzle pieces to form our planet's rocky outer shell. The North American and Eurasian plates are pulling away from each other at a rate of one to two inches a year, gradually unzipping the Atlantic Ocean's floor to form a chain of submarine volcanoes known as a mid-ocean ridge. As the plates pull apart, new material rises from Earth's mantle: a layer of hot, viscous rock sandwiched between the crust and our planet's metal core.

This material partially melts as it rises, supplying Iceland's volcanoes with magma. But it isn't the only source of molten rock in the region. Iceland, like Hawaii, is perched above a "hotspot," a column of heated rock that rises through the mantle, driven by its own buoyancy. This adds yet more fuel to Iceland's volcanic fires.

On the island, this combination of magma sources expresses itself as several different kinds of volcanoes. Hekla's towering cone in the south is closer to the mantle hotspot, whereas the strings of small craters and fissures now forming in Reykjanes's volcanic system are where the plate boundary comes onshore.

"The kind of volcanic eruptions that take place in this area [Reykjanes] are not originating from the typical cone-shaped mountain but more through openings in the crust," says Sara Barsotti, coordinator for volcanic hazards at the Icelandic Meteorological Office (IMO).

These openings occur because the area is located along a kink in the mid-ocean ridge, and the cracks form as a result of the two plates moving apart at an odd angle. Some of these cracks fill with magma, which can eventually erupt; others let chunks of crust slide past one another, leading to earthquakes. Magma moving through the crust can also cause seismic activity as cracks form or widen to accommodate the molten rock.

Fagradalsfjall erupting in 2021

As the mid-ocean ridge widens over millennia, Reykjanes cycles through quiet periods that typically last 800 to 1,000 years before two or three centuries of spectacular eruptions—a period that scientists studying Iceland suspect is starting now. During the 1990s Hreinsdóttir (now at the New Zealand geoscience research and consulting company GNS Science, Te Pū Ao) set up GPS stations throughout the peninsula to monitor the land's slow shifting, bending and buckling, accompanied by small earthquakes. At the time, there were no active eruptions. But looking back, she says these measurements may have captured "the first sign that Reykjanes might be close to coming alive."

Now it seems clear that the peninsula is waking up. Since the late 2000s magma gathering beneath the surface has caused the whole area to periodically inflate and deflate, bulging to accommodate the movements of molten rock underground. Barsotti and her colleagues at IMO track the locations of these bulges, combining this information with data from earthquake sensors, GPS and satellite imagery to try to anticipate which parts of Reykjanes are most primed for future eruptions. Just before the first fissures opened in the 2021 eruption, the final warning sign was a cluster of large earthquakes that shook western Iceland.

After longing to see an eruption since she began her fieldwork on the peninsula around 30 years ago, Hreinsdóttir could only watch her dream come true from afar in 2021, when the COVID pandemic kept her home in New Zealand. This past August, she says, she went on a pilgrimage to lay her hands on the cooled lava from last year—and her six-year-old son was knocked off his feet by a magnitude 4.5 earthquake.

That quake, on August 2, turned out to be a warning for an eruption the very next day that would prove to be even bigger and more spectacular than the one she had missed, although it wouldn't last as long. "It was quite a nice feeling for me," she says. "It felt like Fagradalsfjall was just saying, 'Hello!'"

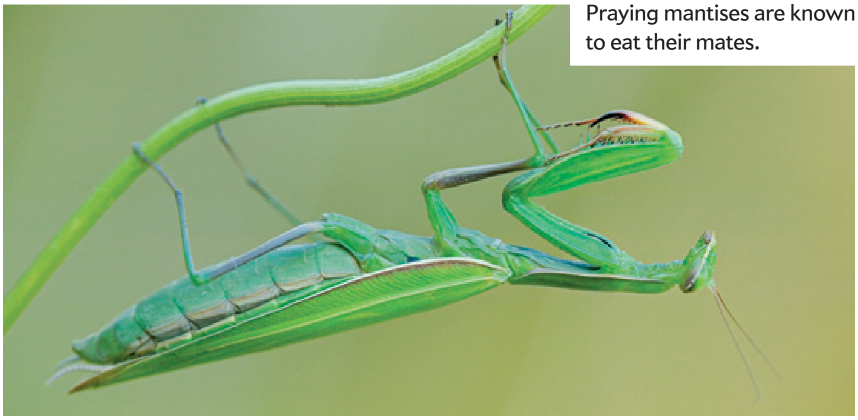
On the day of the eruption, Hreinsdóttir hiked to Meradalir with her colleagues from the University of Iceland, with which she was previously affiliated, and some 1,800 other visitors. All watched the fluorescent orange glow of lava fountaining up from between the rocks of Hreinsdóttir's former study area.

The area stayed active for weeks, and Hreinsdóttir is looking forward to new data on the geochemistry and the speed of the magma coming up, as well as on how the eruption affects the magma of neighboring volcanic systems. And eruptions may occur as often as every few years now that Reykjanes has apparently awakened from its eight-century slumber, offering even more glimpses into the system's inner workings.

"I just wish I could become two to three hundred years old," Hreinsdóttir says, "so that I could watch it for a while."

—Sasha Warren

Jeroen Van Nieuwenhove



Praying mantises are known to eat their mates.

LWA/Getty Images

ANIMAL BEHAVIOR

Biting Distance

What turns animals into cannibals?

From amoebas engulfing one another to polar bears eating cubs, cannibalism is all over the natural world. But it's a risky way to get food. Animals of the same species tend to have similar natural defenses and can easily share diseases. And eating one's own offspring typically undermines genetic success. So what pushes some animals over the edge?

"Almost all predators express cannibalism when conditions get grim enough," says Jay Rosenheim, an entomologist at the University of California, Davis. Some desperate herbivores do, too, he adds. After seeing predatory big-eyed bugs in California cotton fields begin gobbling up their own eggs despite a plethora of available prey, Rosenheim decided to investigate what motivates animals to become cannibals.

"The density of the population is often the key factor that throws that switch," Rosenheim says. For a study in *Ecology*, his team synthesized more than three decades of published research to construct a mathematical model coupling such density to cannibalism.

"It seems so silly, but really, density dependence hasn't been taken into account in a ton of modeling," says Chloe Fouilloux, a researcher at the University of Jyväskylä in Finland, who was not involved in the work but studies cannibalistic frogs. Although some other models include density as a small component, this one focuses primarily on density-related variables such as the frequency of animals encountering one another and the likelihood of a meeting resulting in an attack.

The researchers also catalogued specific ways population density can induce cannibalism. Strained local resources are, unsurprisingly, a key factor: "Hunger is probably the closest thing to a universal or near-universal mediator" of cannibalism, Rosenheim says. The study highlights research suggesting that hunger makes particular neurohormones spike, encouraging aggression—and potentially cannibalistic behavior.

"I was excited to hear about how they are including more recent work on the [physiological] mechanisms underlying cannibalism," Fouilloux says.

Disease spread, spurred by dense populations, can play a role in cannibalistic action as well. A sick animal might become hungry enough to eat its kin. Or a healthy individual could devour sick neighbors, taking advantage of their weakened state. "The interactions of density and disease and cannibalism are really, really complicated," Rosenheim says, adding that the research area is ripe for discovery.

For some animals, the arrival of more of their own kind can trigger cannibalism despite an abundance of other food. This is the case with female big-eyed bugs; when it gets crowded, they start to behave as if their eggs might be from other females. By anchoring the model in real biological conditions such as food scarcity, disease risk and increasing chances of an encounter, Fouilloux says, the researchers showed that density is "this amazing regulating factor that helps explain and contextualize the role of cannibalism in stabilizing population dynamics." —*Fionna M. D. Samuels*

MATERIALS SCIENCE

Silky Solution

Natural material could reduce certain microplastics


Silkworms and cocoons

Salaithip Chaimongkol/EyeEm/Getty Images

Millennia have passed since humans discovered silk and began harvesting it from silkworm cocoons, but scientists are still finding new uses for this remarkable material. Now researchers say it could help tackle a growing environmental and health concern: microplastics, the minuscule plastic fragments that have been found everywhere from mountaintops to the seafloor—and even in the human bloodstream.

Most environmental microplastics form when larger items degrade. But a smaller yet notable portion of the polluting particles is deliberately added to products, according to a report from the European Chemicals Agency. These include microcapsules that protect and gradually release active ingredients in products such as cosmetics and agricultural sprays.

For a study published in *Small,* researchers at the Massachusetts Institute of Technology and chemical corporation BASF developed a silk-based, biodegradable alternative to these capsules. This type of research is urgent for companies that face tightening regulations on deliberate use of microplastics.

Finding substitute materials for intentionally added microplastics is "the only place we are able to really control" microplastic pollution, aside from reducing mismanaged plastic waste overall, says ETH Zürich environmental analytical chemist Denise Mitrano, who was not involved in the study.

Silk is nontoxic, withstands processing and can be sourced from low-quality fiber discarded by the textile industry, says M.I.T. engineer and study co-author Benedetto Marelli. Researchers have proposed other natural compounds to replace intentionally added microplastics, but with these "you cannot check all the boxes at the same time, as we were able to with silk," Marelli says.

The researchers retrofitted existing manufacturing equipment to create micro-

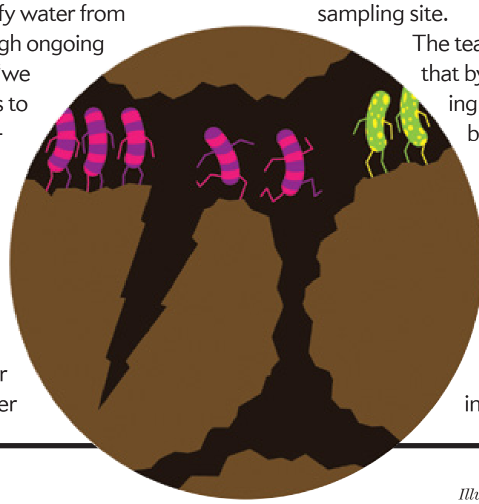
EVOLUTION

Microbe Mixer

Geology meets life deep beneath the ground

Even a mile underground, our planet is teeming with microbes. Scientists long assumed that these subterranean microbial communities, which dwell in aquifers and geothermal wells, saw little ecological change. But recent research suggests that their populations are actually quite dynamic, shifting species composition within days rather than centuries—and geologic activity, such as when rocks split from compression or expansion, could be behind such changes.

Aquatic bacteria and viruses living below Earth's surface are insulated from ecological disruptors such as solar radiation, changes in weather and meteorite strikes. With limited access to nutrients and sunlight, they tend to grow and evolve very slowly. Yuran Zhang, an energy resources engineer at Stanford University, was studying the flow of water between geothermal aquifers when she had the idea to use microbes as a tracer. Because pockets of subterranean water are usually isolated from one another, she and her team thought microbial DNA might act as a good "signature" to identify water from each aquifer. Through ongoing engineering work, "we [already] had access to those valuable samples" of water, Zhang says. "So it worked out."



For a study in *the Proceedings of the National Academy of Sciences USA*, Zhang and her team analyzed water from three boreholes connected to underground aquifers. They took samples once a week over 10 months, sequencing the DNA in each to determine which microbes were present. At first it seemed like each tiny ecosystem's microbial makeup was set in stone. But to the researchers' surprise, those signatures changed rapidly after a rock-fracturing event created cracks at the sampling site.

The team soon realized that by closing and opening tiny channels between these isolated water pockets, fracturing events could completely upend an aquifer's microbial ecology in a matter of days. "Our results are interesting because they

Illustrations by Thomas Fuchs

capsules using the silk protein fibroin that contained concentrated solid forms of an herbicide and the common skin-care ingredient vitamin C. Study co-author Muchun Liu, also at M.I.T., soaked the microcapsules in ethanol for different durations to manipulate how the silk's long protein chains fold and stick together—"tuning" the microcapsules to dissolve and release active ingredients at various desired rates.

To compete commercially, silk-based microcapsules must "perform at the same level, if not better, than the nonbiodegradable counterpart," Marelli says. For example, some sprayed herbicides are released slowly to kill weeds without harming food crops. When tested on corn plants for six days, silk-based microcapsule spray damaged the plants less than an existing commercial product.

Replacing nonbiodegradable microcapsules with silk might not work in every case, but it already looks promising compared with alternatives BASF has investigated, says study co-author Pierre-Eric Millard, a microencapsulation scientist at the company. Products using silk-based microcapsules could be commercially available in a few years if BASF implements them, he adds.

The researchers will next try encapsulating active ingredients that could require a different manufacturing approach, such as those that must remain in liquid or gas forms. —*Ysabelle Kempe*

present not only a different mechanism for community assembly but also a much faster mechanism," says study senior author Anne Dekas, a Stanford microbiologist.

This discovery is exciting, says University of Colorado geomicrobiologist Alexis Templeton, who was not involved in the new research: "There aren't a lot of studies yet that really understand how water is moving through subsurface environments and how it affects the microbiology."

Such research could help scientists predict how to better store potentially hazardous materials such as nuclear waste and carbon dioxide, Dekas says. And it could even aid in the search for extraterrestrial life, because watery moons such as Jupiter's Europa are thought to house similar hard rock aquifers.

It can be tempting to think of geology as completely separate from the realm of life. But according to Templeton, studies like this one "show us how intimately linked the two are." —*Joanna Thompson*

EPIDEMIOLOGY

COVID Relay

New database tracks viral spread among mammals

The virus that causes COVID-19 is a prolific sack of genes that targets not just humans but nonhuman animals as well. And just as humans and animals can infect one another, animals can also infect other animals, says Amélie Desvars-Larrive, an epidemiologist at the University of Veterinary Medicine in Vienna. Scientists have learned a lot about how COVID spreads in humans but less about how it spreads between animals.

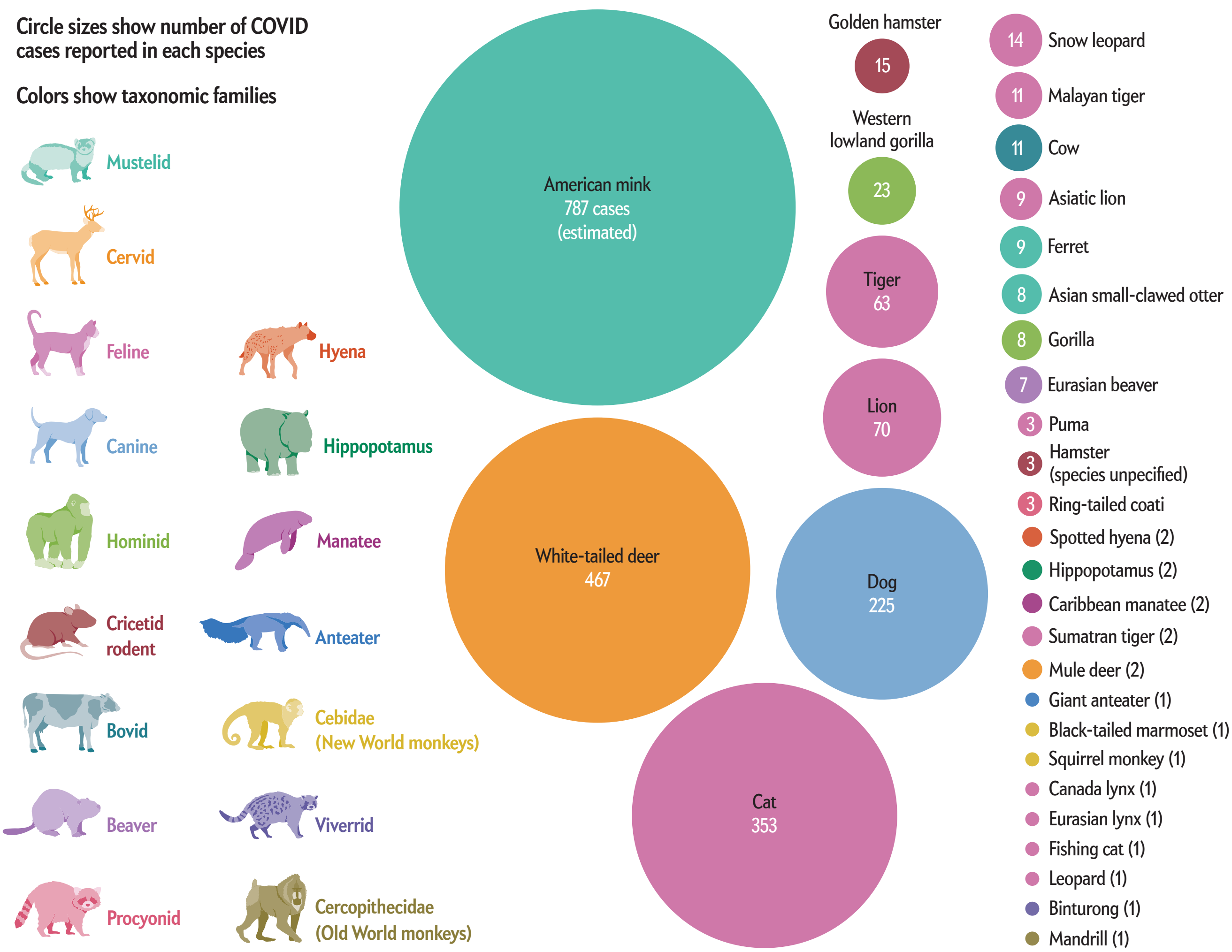
To make it easier to study the connections among humans, animals and the virus, Desvars-Larrive and a team of researchers gathered scattered reports of COVID-infected mammals from all over the world to create a public database. Understanding how the virus spreads between nonhuman mammals, and then between those mammals and humans, can help us better manage the current pandemic—and prepare for the next one.

"We can't continue to focus on humans, to have an anthropocentric point of view on this pandemic," Desvars-Larrive says.

COVID has proved highly contagious among many mammal species: Infections have run rampant among captive mink, and fur farmers have had to kill their entire stocks to stop it. Deer appear particularly susceptible to the virus. Many cat species, both big and small, seem to get it as well. Barbara Han, a disease ecologist at the Cary Institute of Ecosystem Studies in Millbrook, N.Y., who was not involved in the database project, says having this kind of information in one place—rather than split among multiple sources managed by different organizations and government agencies—will likely make it faster and easier for her team to predict how the virus behaves.

The database is growing as more animals are tested and reports shared, and scientists hope it will help them to track animal-to-animal COVID infections as well as transmission between animals and humans. Han says that beyond just tallying individual infected species, the database will make it easier for scientists to study how the COVID-causing SARS-CoV-2 virus affects mammal communities and entire ecosystems.

"People are fascinated that this pathogen is now in [so many] animals and what it might mean for us," Han says. "If we don't have good information about which animals have it now, we can't get those answers." —*Megha Satyanarayana*



Source: SARS-ANI Dataset (as of September 6, 2022) https://github.com/amel-github/sars-ani

Graphic by Brown Bird Design (animals) and Amanda Montañez (data visualization)

PALEONTOLOGY

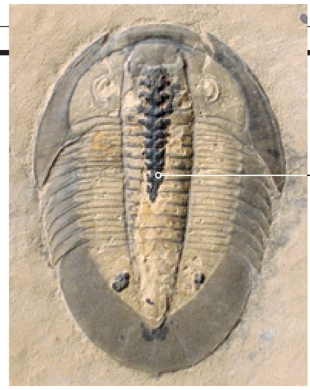
Fishy Business

Rotting fish reveal fossil secrets

If every living thing died right now, by some estimates only around 1 percent would become fossils. Even fewer would have any soft tissues preserved. These rare tissue fossils offer crucial clues about biology and evolution, but their formation remains mysterious. Why do scientists find fossilized intestines, for example, but never a fossilized liver?

Fossils develop when minerals replace the body parts of organisms that die and get buried in sediment, such as the mixture of mud and seawater on the ocean floor. Paleontologists are particularly fond of the fossil-building mineral calcium phosphate because it can preserve soft organs in exquisite detail—sometimes all the way down to cell nuclei. This mineral forms only under specific acidity conditions, so scientists have hypothesized for decades that differences between decaying organs' pH levels determine which ones get preserved.

To better understand how organs change after death, University of Birmingham paleontologist Thomas Clements made a trip to the fishmonger with a plan to ruin four delicious seabass. His team poked pH probes into the fishes' internal organs, then submerged the carcasses in artificial seawater and let them rot.



Rudy Lerosey-Aubril/Harvard University

For 70 days the researchers watched the seabass bloat, shed their flesh and disintegrate into piles of bones while the probes monitored the body parts' changing chemistry. The results, recently published in *Paleontology*, show that within 24 hours every organ's acidity reached the right range for calcium phosphate to crystallize, with these conditions lasting up to five days. The team had expected to find stark differences between organs, but instead the whole carcass rotted evenly into a relatively homogeneous soup of decay by-products, held inside by the skin for up to 20 days.

This surprising result prompted the researchers to consider other factors that could aid fossilization, such as phosphorus levels within an organ's tissues. "Muscles are full of phosphate," Clements says. "If you have the phosphate already there, then there's already a high likelihood that [the organ] will be replaced by calcium phosphate."

"It would be interesting to do this in [non-fish organisms] as well," says paleontologist Victoria McCoy of the University of Wisconsin–Milwaukee, who was not involved in the study. She suggests future work could monitor other aspects of the environments within decaying organs, such as concentrations of various elements. Researchers could also investigate whether tissues' physical structures influence mineral formation. "In many ways, it brings up more questions than there would have been if they found organ-specific pH gradients," McCoy says. "But that's what makes it so cool." —*Sasha Warren*

NEWS AROUND THE WORLD

Quick Hits

By Fionna M. D. Samuels

BULGARIA
Scientists determined that two teeth, left uncatalogued in a museum for decades, belong to a long-extinct European panda. The beast likely lived in a swampy forest, a radically different habitat from that of its bamboo-eating modern cousins, and had a more diverse diet.

KENYA
The worst drought in 40 years killed 179 elephants—20 times more than poachers did in the past year—making climate change the bigger threat to the animals.

LIBYA
Genome sequencing of 6,000-year-old seeds from a watermelon relative suggests the fruit was prized for these nutritious seeds, not for its flesh—which was bitter, unlike today's refreshingly sweet varieties.

MEXICO
A new species of giant deep-sea isopod—a cousin to the common pill bug but more than 10 inches long—was found hiding in plain sight. Originally captured off the Yucatán Peninsula, it was confused with other isopods in an aquarium until genome sequencing revealed it was something new.

TANZANIA
Social media is coming to the heights of Mount Kilimanjaro with the installation of high-speed fiber-optic Wi-Fi. Although the new system could make it easier for climbers to post selfies or call for help, people living in the mountain's shadow will not have expanded coverage.

TURKEY
Skeletal DNA from more than 700 people who lived in Anatolia 10,000 years ago suggests that agriculture developed as different migrating populations intermingled, rather than solely from local hunter-gatherers switching to farming. These migrations may also have brought Indo-European languages to the region.

For more details, visit www.ScientificAmerican.com/nov2022/advances

TECH

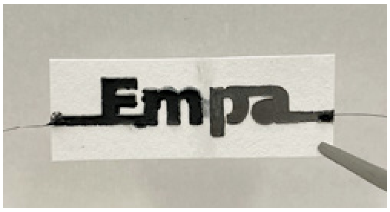
Paper Battery

A paper-and-water battery could reduce e-waste

Discarded electronics are piling up fast, pushing researchers to explore creative ways to reduce this e-waste. Now one team has crafted a water-activated disposable battery made of paper and other sustainable materials.

The wires, screens and batteries that make up our devices—not to mention the plastic, metal and other materials that encase them—are filling up landfills with hazardous debris. Some e-waste is relatively large: old flip phones and air conditioners, for instance. Other e-waste is more insidious, such as electronic single-use medical diagnostic kits, environmental sensors, and smart labels that contain disposable batteries and other equipment.

"It's these small batteries that are big problems," says University of California, Irvine, public health scientist Dele Ogunseitan, who is a green technology researcher and adviser for major tech companies and was not involved in developing the battery. "Nobody really pays attention to where they end up."



Researchers at the Cellulose & Wood Materials Laboratory at the Swiss Federal Laboratories for Materials Science and Technology (Empa) are working to address this problem. Their new paper in *Scientific Reports* describes a water-activated paper battery developed from environmentally friendly materials that could eventually present a sustainable alternative to the more harmful batteries common in low-power devices.

The paper battery has the same key components as standard batteries but packages them differently. Like a typical chemical battery, it has a positively charged side called a cathode, a negatively charged side called an anode, and a conductive material called an electrolyte between the two. A traditional battery's components are encased in plastic and metal; in the new battery, the anode and cathode are inks printed onto the front and back of a piece of paper. That paper is infused with salt, which dissolves when the paper is dampened with water. The resulting saltwater solution acts as the electrolyte.

Sustainable materials were a prerequisite for the researchers, who considered only nontoxic and abundant ingredients to create their device. "We were fairly confident that we would have something that would work in the end, but developing these materials and ink systems is far from trivial," says Gustav Nyström, head of the Cellulose & Wood Materials Laboratory and senior author of the study. After trying hundreds of formulations for the battery components, the researchers settled on a graphite ink to make the cathode, a zinc ink for the anode, and salt-infused paper to create the electrolyte.

When the paper is dry, the battery is shelf-stable. Add just a couple of drops of water, however, and the engrained salt dissolves, allowing electrons to flow. Once the paper is moistened, the battery activates within 20 seconds. At that point, if the battery is not connected to an electronic device, it has a consistent voltage of 1.2 volts. (For comparison, AA batteries have a voltage of about 1.5 volts.) The new battery's operating performance declines as the paper dries. When the scientists rewet the paper during testing, the battery regained functionality and lasted an hour before beginning to dry out again.

Although the researchers demonstrated that their battery could power an alarm clock, disposable paper batteries are unlikely to replace standard AAs on store shelves. Instead Nyström envisions a future where these batteries are embedded in diagnostic tests and environmental sensors, ideally with other sustainable components such as screens and packaging.

That future may not be so far off. It is hard to predict a time line for manufacturing such items at scale, but Nyström says he is in contact with potential industry partners and believes these batteries could make their way into products within the next two to five years. "The performance that you see on this device, I think, is sufficient for a lot of these applications already," he says. It is mostly a matter of scaling up production and integrating the batteries into systems such as diagnostic tests and environmental sensors.

"This is work that really starts with the development of sustainable materials," Nyström explains. From there, he says, "I think we were able to create something that is quite useful." *—Anna Blaustein*

Alexandre Poulin

ANIMAL BEHAVIOR

Name Check

Expressive identity sounds set dolphins apart


Bottlenose dolphins

Flip Nicklin/Minden Pictures

Dolphins' "signature whistles," which they use like names to identify themselves to others and convey personal information, have long been known as one of the most complex forms of animal communication ever studied. New research quantifies just how much these calls can vary between individuals and situations.

Experts can determine a dolphin's signature whistle over time by listening as it calls out to its peers. The animals vary these whistles widely, repeating sections in loops, altering the pitch, and adding and deleting short segments. A new study, published in *Frontiers in Marine Science*, evaluates these changes through a database of nearly 1,000 recorded whistles, collected from around 300 individual dolphins over four decades.

To calculate the signature whistles' variability and allow comparison with sounds from other species (particularly birds), the authors used a statistical metric that evaluates 21 different facets of a sound—such as length, frequency, pitch and pattern. The more each individual varied the facets in each call, and the more the calls varied between different individuals, the higher the species scored. Bottlenose dolphins' identification sounds had the largest audio palette in a recent comparison paper, followed by larks'; researchers do not yet have a consensus on how humans measure up.

This metric is good for comparing across species, says Woods Hole Oceanographic Institution marine biologist Laela Sayigh, the dolphin study's lead author. But she notes that the 21 facets barely scratch the surface of dolphin whistles' true complexity. "It's actually kind of phenomenal," Sayigh says, that even using this "coarse" metric, "dolphins are the most individually distinctive communicators."

University of South Bohemia behavioral ecologist Pavel Linhart, who was not involved with the study but led the interspecies comparison, says he is glad the researchers tallied this variability. "I think because it was just so obvious that it's so easy to identify [individuals], they didn't quantify it before," he adds.

Scientists are just beginning to explore dolphins' reasons for varying their signature whistles—possibly to express emotional states, for one. Future work will help decipher shared, nonsignature whistles that dolphins also exchange, Sayigh says. "We're really in the infancy of understanding those."

—*Rebecca Dzombak*

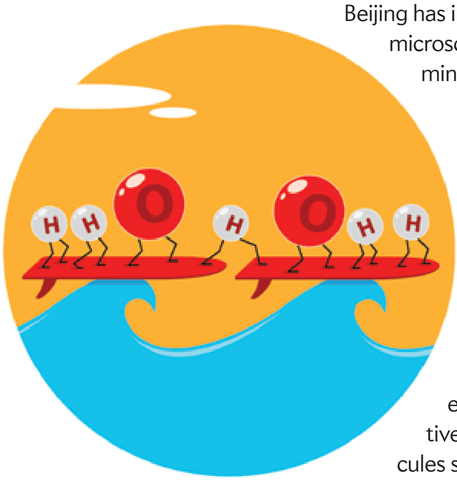
CHEMISTRY

Water Network

The first images of two elusive water ions prove decades of theory correct

To make efficient hydrogen energy technology a reality—from generating hydrogen through electrolysis to next-generation chemical fuel cells—scientists need to know exactly how individual hydrogen atoms move through water.

A neutral water molecule comprises two hydrogen atoms bonded to a single oxygen atom, the entire structure bending to give the molecule a partially positive side and a partially negative side, like a magnet. If you could zoom in on a glass of water, you would see trillions of such molecules, along with some excess individual hydrogen atoms that have lost their electrons (in other words, just protons). For 200 years researchers have theorized that these protons hop from one water molecule to another by attaching to the nearest molecule and kicking off one of the protons already bonded there. This proton then bonds with the next neighbor. Now a team of scientists in Beijing has imaged such particles under a microscope for the first time, helping illuminate how these jumps occur.



Models predicted that this process most often happens in two ways. In one, a proton bonds directly to a single water molecule, turning it from a neutral molecule into a positive ion. Three surrounding neutral water molecules orient so their partially negative sides stabilize this charge. In the other option, the extra proton sits between the negative ends of two neutral water molecules so that each shares the burden of the positive charge.

Researchers were able to verify these orientations through atomic-force microscopy—a technique that generates images by tracing the nanoscopic point of a specialized needle over bumps on a surface. Using this instrumentation, Jing Guo, a chemist at Beijing Normal University, and her colleagues imaged a molecule-deep network of water frozen onto a slip of metal and revealed how extra protons changed that network. Their work was published in *Science*.

Incredibly sensitive measurements were needed to differentiate between the two water configurations. "The position of protons along the hydrogen bond differed only by about 20 picometers," Guo says—less than half the length of a hydrogen atom itself. "We are very, very excited to figure out the underlying pictures after long struggles."

The team found that these two configurations occurred at different frequencies and ratios depending on what kind of metal the water was frozen to. They also used electricity to force water to flip-flop between the different setups. "It's very astounding that they can [directly] observe these things," says Thomas Kuhn, a theoretical chemist at Paderborn University in Germany, who was not involved in this work. "It opens the door to study the mechanisms behind [hydrogen generation]," he says. "And maybe out of that, good stuff comes."

—Lars Fischer and Fionna M. D. Samuels

BIOMECHANICS

Science in Images

By Darren Incorvaia

Carnivorous plants' peculiar strategies for snagging live prey have long captured the public imagination. But even within this strange group, in which food-trapping mechanisms have evolved multiple times independently, some oddities stand out. For example, the visually striking pitcher plant *Nepenthes gracilis,* native to Southeast Asia, can harness falling rain's energy to ambush animals. A new study in *Biology Letters* demonstrates how the structure of the plant's pitcher component, itself a modified leaf, makes the unusual strategy work.

"This is the only case we know where a plant actually exploits [external energy] for a purpose," says study co-author Ulrike Bauer, an evolutionary biologist and biomechanist at the University of Bristol in England. But how does this rain-powered trap function?

This species' pitcher has a rigid, horizontal lid with an exposed underside that secretes nectar, luring insects to alight on it. When a raindrop strikes the lid's top, the lid jolts downward and flings any unsuspecting visitor into digestive juices below. Bauer and study lead author Anne-Kristin Lenz, also at Bristol, used high-resolution x-ray scans to analyze cross sections of the pitchers when the lid is raised, lowered, and in a neutral position. Their results revealed a structural weak point, which the researchers called a torsional spring, in the pitcher's neck: when a raindrop hits the lid, the weak spot buckles and forces the lid to flick downward, similar to a diving board. The weak point makes the pitcher's body bend and snap back in a specific, consistent way, so the lid raises back up without bouncing too far—unlike a typical leaf's chaotic oscillations when struck by rain. The researchers also found that a closely related pitcher plant, *Nepenthes rafflesiana,* lacked this mechanism.

"This is a really nice study that is comparing two species and getting back to this diversity among them," says Pennsylvania State University entomologist Tanya Renner, who was not involved with the research. Although the rain-trap technique so far seems unique to *N. gracilis,* Renner hopes future work will examine more of the extensive diversity seen in carnivorous plants. "Personally," she says, "I would look at more species."

To see more, visit ScientificAmerican.com/science-in-images

Paul Starosta/Getty Images

Jane Hirshfield, a member of the American Academy of Arts and Sciences, is a poet, essayist and translator whose work speaks to the crises of the biosphere, justice and interior life. Her 10th poetry collection, *The Asking: New & Selected Poems,* due from Knopf in September 2023, will include "Mosses."

Mosses

"In the Mojave Desert, a translucent crystal offers bryophytes much-needed respite from the heat of the sun."
—New York Times

For hypolithic mosses,
it seems,
four percent of daylight is right.
They live, the headline says,
by sheltering
under a parasol of translucent quartz.

The crystal scatters
the light's ultraviolet,
dilutes its heat,
traps the night's condensed moisture
to moss-sized rain.

I think of these mosses
and consider.
Perhaps we, too, are mosses,
evolving to the parch
of our self-made Mojaves.

Unable to bear the full brightness,
the full seeing.

To recognize fully the Amazon burning,
the Arctic burning,
the Monarchs' smoke-colored missing migration.

An experiment not meant to last.

And yet we found shelter within it,
we pondered our lives and the lives of others,
thirsted, slept.

To the implausible green of existence,
for-better, for-worse,
we offered our four-percent portion of praises,

for-better, for-worse
our four-percent portion of comprehension.

Jenna T. B. Ekwealor

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic*. She was science editor at *Time* and managing editor of *Scientific American Mind*.

Gas Stove Worries

Evidence is building that these popular appliances pose health hazards

By Claudia Wallis

I love my gas stove. There's nothing quite like cooking over that beautiful blue flame, so quickly adjusted with a flick of a dial and so suited to its purpose that when things are going well in life, we say we are "cooking with gas." But in recent years environmentalists have been warning that gas stoves are bad for the climate and not so great for our health, either. Two new studies out this year have heightened health worries about noxious fumes in our kitchens. Is the evidence sufficient to alter our cooking habits? For me, the answer is yes—in some modest ways; others will want to judge for themselves.

Broadly speaking, there are two categories of concerning emissions related to gas stoves. First, there is the unburned natural gas that can escape before the flame ignites or leak from a gas hook-up. This gas is more than 90 percent methane. Second, there are the pollutants created by combustion when a burner is on, most notably nitrogen oxides, which can irritate the lungs.

The big surprise in one new study, conducted by environmental scientists at Stanford University, was the amount of unburned gas that leaks into kitchens when a stove is off. They found that more than three quarters of methane that escapes from a stove does so when it is not in use, most likely through imperfect pipe fittings. Only one out of 53 stoves measured for the study—and many more the team has measured since—did not leak when turned off, says Rob Jackson, senior author of the study. Methane is not toxic, but it is a potent greenhouse gas. With 40 million gas stoves across the country, Jackson and his co-authors estimate that the heat-trapping potential of the methane they discharge annually is roughly equivalent to the carbon dioxide released by half a million gas-powered cars.

The Stanford study also looked at the amount of nitrogen oxides produced when using the stoves. In a matter of minutes, families who do not use their exhaust hoods and who have small, poorly ventilated kitchens can surpass the Environmental Protection Agency's outdoor exposure limit for nitrogen dioxide of 100 parts per billion (ppb) per hour. (The EPA does not have an indoor safety standard for these gases.) Even short exposures to excess nitrogen dioxide can aggravate symptoms in people with respiratory conditions. And there is substantial evidence that long-term exposure raises the risk of developing asthma.

The second study, conducted in the Greater Boston area, looked at the nonmethane components of unburned gas from stoves. They found trace quantities of 21 chemicals considered hazardous by the EPA, including benzene and other volatile organic compounds (VOCs). The amounts were small, but this understudied issue warrants more attention, says lead author Drew Michanowicz, a senior scientist at PSE Healthy Energy, a nonprofit research and policy group. "A lot of us work at home now. We take about 20,000 breaths a day, and my stove is like 10 feet away from me. What else is in natural gas?" Michanowicz also worries that as more people weatherize their homes and seal windows, "you are reducing air exchange, which means indoor pollution will be magnified."

Not surprisingly, the American Gas Association, an industry group, has criticized both studies. The levels of VOCs found in the Boston study are "reassuringly low," says Richard Meyers, a vice president of the association, noting that the authors "identified no health concern." As for the Stanford study, Meyers says the nitrogen oxides were measured improperly, using plastic sheets to create small spaces around the stoves. Stanford's Jackson replies that the tenting was done only in large kitchens to aid in measuring the rate of gas release, and the team's health risk assessments were based on measurements in open, untented kitchens.

What is the average home cook to make of all this? They might take a cue from Michanowicz, who bought a plug-in countertop induction burner and does much of his cooking on that $100 item. Jackson, for his part, is putting his money where his research is: "I'm replacing a perfectly good gas stove" with an induction stove. He would like governments to provide incentives for people to switch to electric ranges. Several U.S. cities are curtailing the use of natural gas (for stoves and heat) in new construction.

As for me, I'm making some changes. I've switched to an electric kettle for boiling water, and despite its annoying noise, I now use the exhaust hood over my stove—something only about 25 to 40 percent of people say they do. And weather permitting, I'll open a window. SA

Illustration by Diana Bolton

THE FRONT FACE of the Thwaites Ice Shelf towers up to 40 meters above the sea. The slab of floating ice is rapidly weakening.

CLIMATE CHANGE

The Coming Collapse

Two expeditions to Antarctica's Thwaites Ice Shelf have revealed that it could splinter apart in less than a decade—allowing a vast glacier behind it to slide into the sea

By Douglas Fox

Photograph by Elizabeth Rush

Douglas Fox writes about biology, geology and climate science from California. He wrote the July 2021 article "The Carbon Rocks of Oman," about efforts to turn carbon dioxide into solid minerals.

ON DECEMBER 26, 2019, ERIN PETTIT TRUDGED ACROSS A PLAIN OF GLARING SNOW AND ice, dragging an ice-penetrating radar unit the size of a large suitcase on a red plastic sled behind her. The brittle snow crunched like cornflakes underneath her boots—evidence that it had recently melted and refrozen following a series of warm summer days. Pettit was surveying a part of Antarctica where, until several days before, no other human had ever stepped. A row of red and green nylon flags, flapping in the wind on bamboo poles, extended into the distance, marking a safe route free of hidden, deadly crevasses. The Thwaites Ice Shelf appeared healthy on the surface. But if that were the case, Pettit wouldn't have been there.

Pettit was studying defects within the ice, akin to hidden cracks in an enormous dam, that will determine when the ice shelf might crumble. When it does, the rest of the West Antarctic Ice Sheet behind it could flow right into the ocean, pushing up sea levels around the planet, flooding coastal cities worldwide.

From a distance, the ice shelf looks flat, but as Pettit walked she saw the guide flags ahead of her rise and fall against the horizon—a sign that she was walking across an undulating surface. To Pettit, a glaciologist at Oregon State University in Corvallis, this was significant. It meant that the ice's underside was a rolling landscape—not what anyone expected. In satellite images, the center of the ice shelf looks stable. But it isn't, Pettit says: "There are five or six different ways this thing could fall apart."

The Thwaites Ice Shelf begins where the massive Thwaites Glacier meets the West Antarctic coast. The shelf is a floating slab of ice, several hundred meters thick, extending roughly 50 kilometers into the Southern Ocean, covering between 800 and 1,000 square kilometers. For the past 20 years, as the planet has warmed, scientists using satellites and aerial surveys have been watching the Thwaites Ice Shelf deteriorate. The decline has caused widespread alarm because experts have long viewed the Thwaites Glacier as the most vulnerable part of the larger West Antarctic Ice Sheet. The ice shelf acts as a dam, slowing its parent glacier's flow into the ocean. If the shelf were to fall apart, the glacier's slide into the sea would greatly accelerate. The Thwaites Glacier itself holds enough ice to raise the global sea level by 65 centimeters (about two feet). The loss of the Thwaites Glacier would in turn destabilize much of the rest of the West Antarctic Ice Sheet, with enough ice to raise sea levels by 3.2 meters—more than 10 feet.

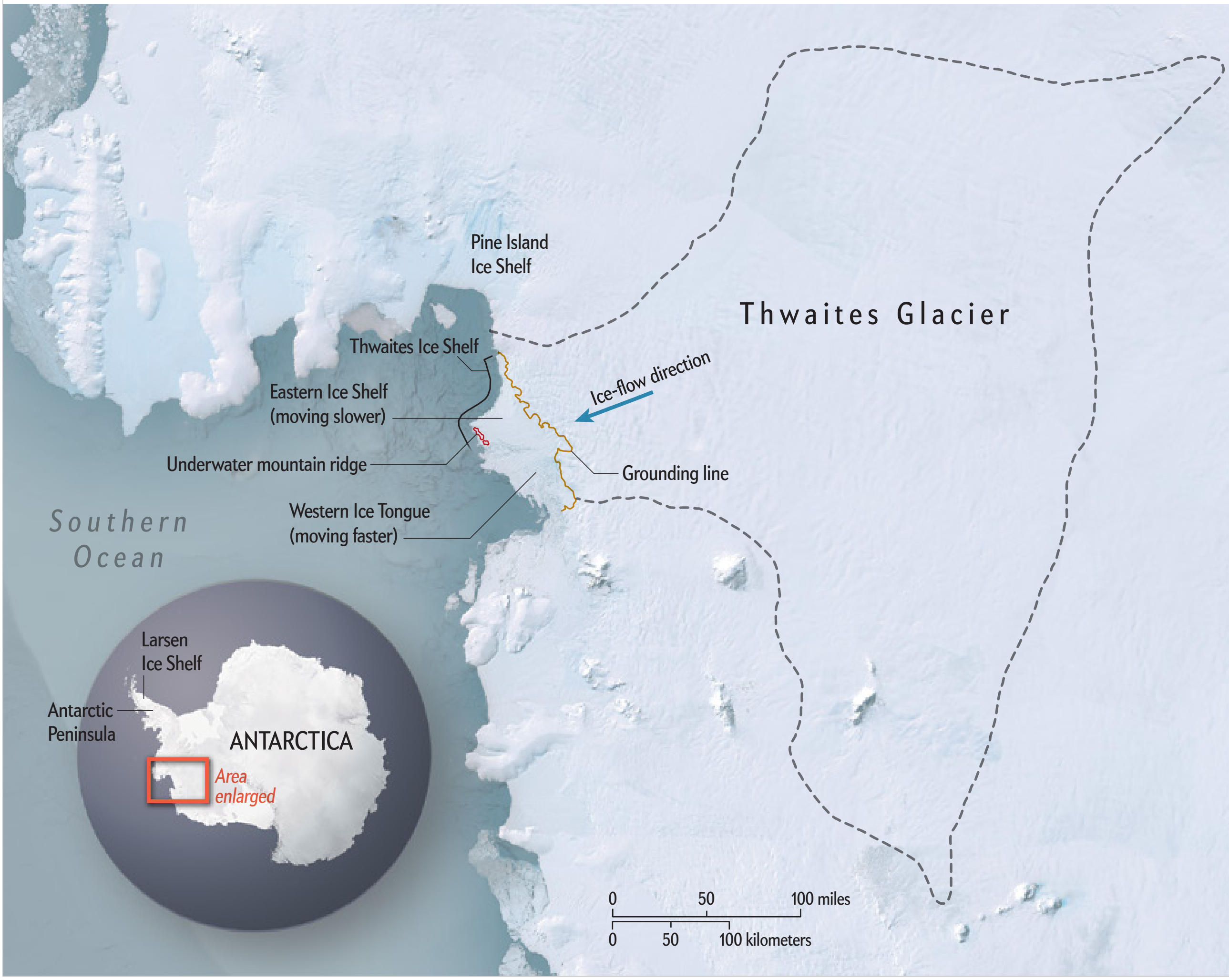
Even the most optimistic greenhouse gas emissions scenarios indicate that by 2050 humanity will likely be locked in to at least two meters of sea-level rise in the coming centuries. That will put the homes of at least 10 million people in the U.S. below the high tide line. If the Thwaites Glacier collapses and destabilizes the heart of West Antarctica, then sea-level rise jumps to five meters, placing the homes of at least 20 million U.S. people and another 50 million to 100 million people worldwide below high tide. Although Sacramento, Calif., is not the first city that comes to mind when imagining sea-level rise, it would lose 50 percent of its homes as ocean water pushes 80 kilometers inland through low-lying river deltas. The fate of thousands of coastal towns worldwide hangs on events unfolding in Antarctica right now.

Since 1992 the glacier has hemorrhaged a trillion tons of ice. It is currently losing an additional 75 billion tons of ice every year, and the rate is increasing. What happens next, however, depends on processes that can't be studied from the air—flaws within the shelf that could break it apart, accelerating the glacier's demise. That's why, in 2018, the British National Environmental Research Council and the U.S. National Science Foundation launched a $50-million effort called the International Thwaites Glacier Collaboration to study the glacier and its ice shelf up close.

The collaboration involved eight research teams, including one that reported this September that the glacier was retreating faster than had been predicted just a few years ago. Two of the teams visited the Thwaites Eastern Ice Shelf between November 2019 and January 2020. Pettit's team examined the central part of the shelf, looking at structural defects and ocean currents underneath. I accompanied her team as an embedded journalist, earning my keep with unskilled labor, much of it involving a snow shovel. Another team investigated the back edge of the ice shelf along the continent's submerged shore, sending a remotely operated submarine down a narrow hole to explore a crucial en-

Thwaites Glacier, Ready to Flow

Antarctica's Thwaites Glacier, about the size of Nebraska, slowly flows into the Southern Ocean. It is held back by the Thwaites Ice Shelf, which is braced by the seafloor along the grounding line and by underwater mountain peaks at sea. The shelf is fragmenting, however, speeding the glacier's demise, which would raise global sea level by 65 centimeters (about two feet).

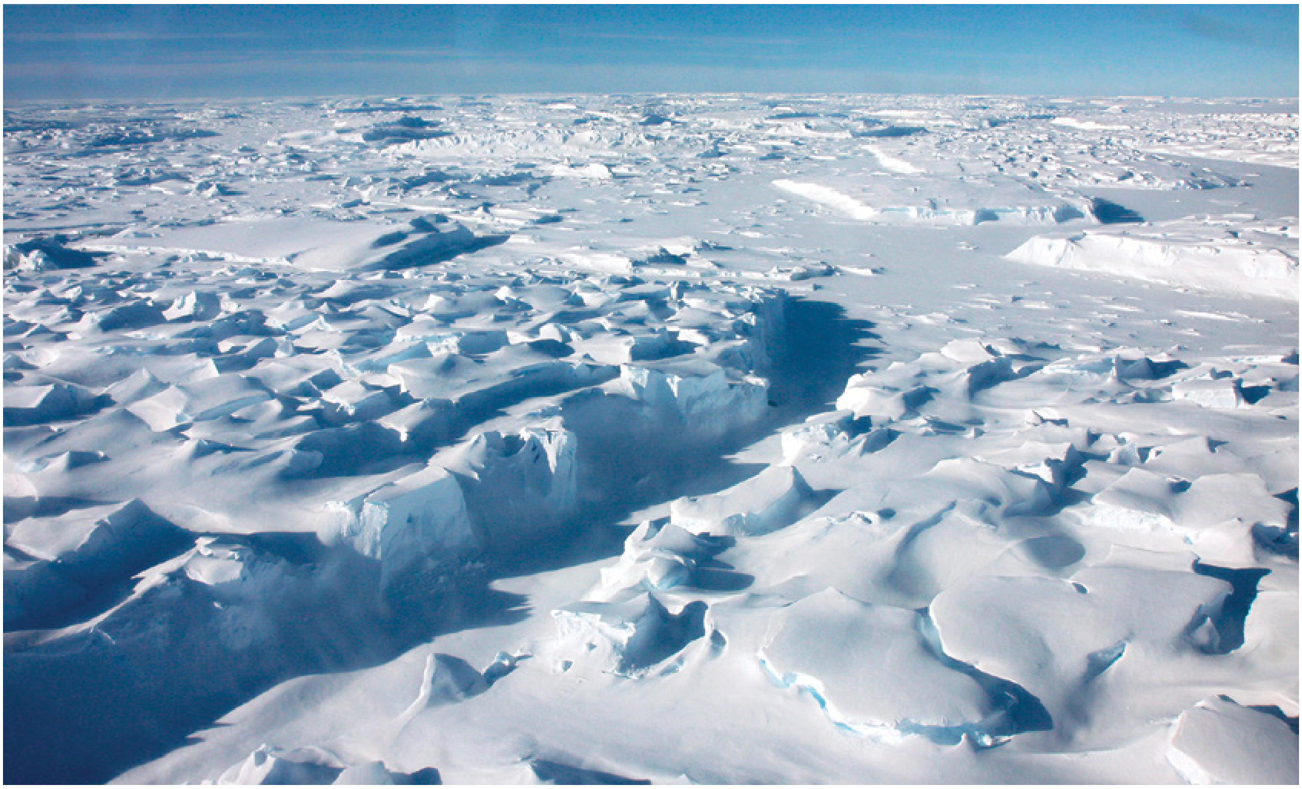


vironment hidden under 600 meters of ice, where the shelf is melting most quickly. The results paint a worrisome picture. The ice shelf "is potentially going to go a lot faster than we expected," Pettit says.

ANTARCTICA'S ICE SHEET HAS CONSISTENTLY SURPRISED THOSE WHO study it. In February 1958 researchers in West Antarctica, 700 kilometers inland from the coastline, drilled four meters into the snow, lowered in 450 grams of explosives and detonated it with a muffled *fuff* that sprayed snow in the air. Geophones sitting facedown on the ice recorded the sound waves that reflected off the hard ground far below. By measuring the return time, Charles Bentley, then a graduate student at Columbia University, made a shocking discovery: the ice in this location was more than 4,000 meters thick—several times thicker than anyone expected—and rested on an old ocean floor 2,500 meters below sea level.

By the 1970s researchers were flying ice-penetrating radar in airplanes that crisscrossed the region. The scattered surveys confirmed that the West Antarctic Ice Sheet sits in a broad basin, deepest toward the center, with large glaciers spilling into the sea through gaps in the basin's outer rim. Even as scientists testified to Congress in the late 1970s about carbon dioxide and the dangers of global warming, most of them didn't think that Antarctica would lose its ice anytime soon. But in 1978 John Mercer, a glaciologist at the Ohio State University, sounded the alarm that West Antarctica represented "a threat of disaster." If the ice sheet lost the shelves separating it from the sea, it might crumble far more quickly than people imagined. Three years later Terry Hughes, a glaciologist at the University of Maine, called out two specific coastal glaciers—Thwaites and Pine Is-

Map by Mapping Specialists



THE WESTERN ICE TONGUE of Thwaites has splintered into hundreds of icebergs, which look like raised plateaus, interspersed with sea ice perhaps a meter thick, all covered in snow.

Douglas Fox

land—as "the weak underbelly" where the collapse of the ice sheet would most likely begin. A pair of papers published in 1998 and 2001 by Eric Rignot, a glaciologist at NASA's Jet Propulsion Laboratory, showed that these two glaciers were indeed thinning, melting from beneath, allowing ocean water to intrude farther inland under the ice.

Additional aerial surveys since then have shown that the Thwaites Glacier is especially troubling. The ground underneath the glacier is a relentless slope that drops deeper as it moves inland from the outer, seaward edge, allowing warm ocean water to slide under the glacier, melting it from below. As the ice thins, losing weight, it is also expected to lift off the bed and float on the intruding warm, dense water, allowing the water to penetrate even farther—eventually reaching the 2,500-meter trench at the heart of the continent. If that happens, "you're going to unload the West Antarctic Ice Sheet," says Ted Scambos, a glaciologist at the University of Colorado Boulder, who traveled with Pettit's team in 2019–2020.

The glacier flows into the sea in two arms that move at different speeds. The "fast arm" on its western side is a fragile, floating "ice tongue." In satellite images it resembles a shattered windshield, composed of hundreds of icebergs a kilometer or two across drifting into the ocean. The "slow arm," on the glacier's eastern side, is a smaller ice shelf that for years seemed more stable. The front edge butts into a submarine mountain ridge 40 kilometers off the coast. This ridge acts like a doorstop, creating back pressure that holds the ice shelf together.

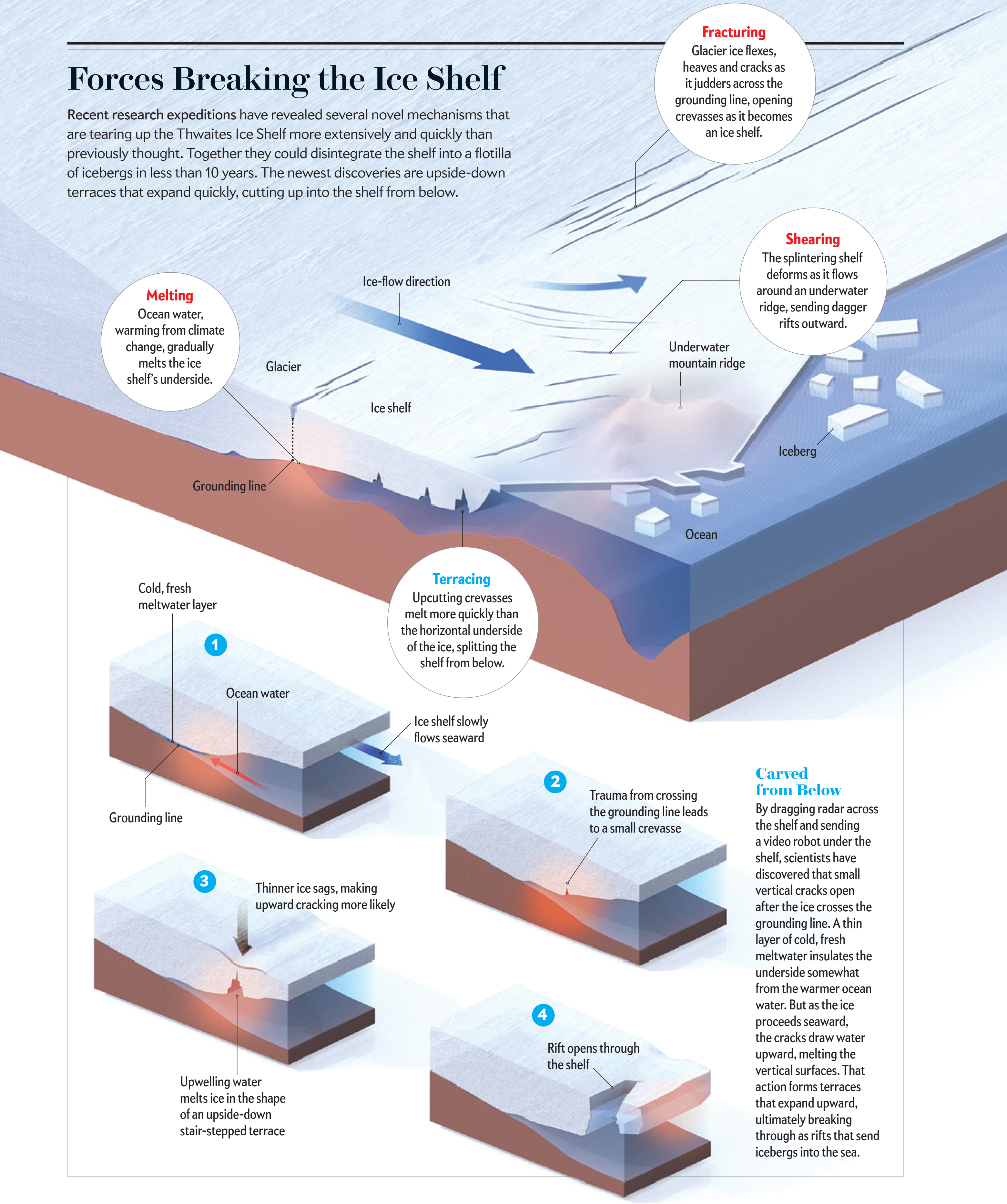
Pettit and her team chose the mountain-buttressed eastern shelf for their expedition. In satellite images, the shelf's central region appeared relatively stable, its surface smooth enough for small ski-mounted planes to land. A pair of mountaineers could scout for hidden crevasses and establish safe routes, allowing the team to move around freely. Pettit worried that visiting an apparently undamaged part of the ice shelf might limit their opportunity to learn something new. She didn't need to worry.

ANTARCTIC FIELDWORK REQUIRES SENDING TONS OF FUEL, FOOD and survival gear ahead of time. The field team has to be supported by layers of transport, workers and staging camps. All told, the Thwaites research expeditions required several hundred thousand kilograms of equipment and supplies delivered by ships, planes and convoys of tractors towing sleds across hundreds of kilometers of ice that had been searched ahead of time for crevasses. The British Antarctic Survey and the U.S. Antarctic Program staged some of that gear a year or two in advance. But in Antarctica, even this kind of preparation isn't enough to avoid complications.

In September 2019, two months before I joined Pettit's team as they departed for the frozen continent, they received new satellite images showing two new rifts in the ice shelf. These "daggers" originated where the ice collides with the undersea mountain; the rifts had surged inward toward the coast, to within five kilometers of our planned destination. Expedition leaders worried that one of these rifts could rip through the camp, but the team decided to press forward, with a colleague back home tracking the rifts via satellite. After a series of storms delayed the expedition by a few weeks, we reached the Thwaites Eastern Ice Shelf in mid-

Forces Breaking the Ice Shelf

Recent research expeditions have revealed several novel mechanisms that are tearing up the Thwaites Ice Shelf more extensively and quickly than previously thought. Together they could disintegrate the shelf into a flotilla of icebergs in less than 10 years. The newest discoveries are upside-down terraces that expand quickly, cutting up into the shelf from below.



Carved from Below

By dragging radar across the shelf and sending a video robot under the shelf, scientists have discovered that small vertical cracks open after the ice crosses the grounding line. A thin layer of cold, fresh meltwater insulates the underside somewhat from the warmer ocean water. But as the ice proceeds seaward, the cracks draw water upward, melting the vertical surfaces. That action forms terraces that expand upward, ultimately breaking through as rifts that send icebergs into the sea.

Graphic by Violet Frances for Bryan Christie Design

December 2019. We assembled a row of tents, protected from the constant easterly winds by walls of snow blocks shoveled and handsawed from the landscape, and set up gear for what would be a month of arduous work to come.

The first couple of days were relatively warm. Our boots plunged deeply into the slushy snow, and puddles of meltwater pooled up along the tents. A series of giant ice cliffs, eight kilometers away, were visible to the south. Those upheavals marked the zone where the ice cracked and flexed as it transitioned from a grounded glacier into a floating ice shelf.

As the weather cooled and the snow hardened, Pettit made her first long walks, dragging her radar along preplanned lines. The radar provided two-dimensional profiles of the ice shelf's internal layers, like the slices of a hospital MRI scan. Those first glimpses proved far more interesting than Pettit expected.

Her radar showed that layers in the top 25 meters of the shelf were smooth and mostly flat, but below that they suddenly turned jagged. Pettit speculated that the jagged layers had been part of the ice when it juddered across the rocky coastline bed and started to float seaward, perhaps 15 years before; they were forever imprinted with the trauma of that transition. The smooth layers represented snow that had fallen on top since then, when the ice was afloat.

More surprising, Pettit found that the shelf's underside—a place that human eyes had never seen—looked strangely ordered, as if it had somehow been sculpted intentionally. The underside was corrugated with a series of trenches that ran perpendicular to the direction of ice flow, like waves offshore from a beach. Each trench was 500 to 700 meters wide and cut as far as 50 meters up into the ice, the height of a 12-story building. "These things are huge," Pettit told me. Oddest of all, the trench walls weren't smooth, as one might expect of melting ice. They were stair-stepped terraces, with a series of vertical walls each five to eight meters tall, like the sides of an open-pit mine. "We don't know what these stepped things are," she said.

These stair-stepped trenches had escaped detection in previous surveys. Airborne radar measurements are taken from planes moving at least 150 kilometers per hour, so each reading is an average over a long swath of ice. Pettit dragged her radar at a stately three kilometers per hour, allowing her to capture a much finer-grained picture.

As Pettit was getting her first look at the strange terraced structures, her colleagues were starting to see hints of another unexpected observation: the bottom of the ice was not melting the way they expected. On January 2, I wolfed down a breakfast of dehydrated porridge with Christian Wild, a postdoctoral scholar who works with Pettit. He and I then drove a snowmobile out into a frigid snowfall. The sound of the engine was muffled, and the wan light seemed to seep in from all directions, leaving no shadows, no texture and no hint of the approaching bumps that we trundled over. We steered along our GPS line, with just enough visibility to see each new flag appear silently into view, then dissolve behind us in a gentle slurry of snowflakes.

At a series of stops, Wild used high-precision radar to measure the thickness of the ice shelf, accurate to a few millimeters. He had already measured the same points a week earlier. Because satellite estimates suggested the ice shelf was thinning an average of two or three meters per year, he expected to find the ice three to six centimeters thinner than the week before. To his astonishment, he saw almost no thinning. "It doesn't make any sense," he said toward the end of a long day.

Back at camp, other team members prepared to measure the temperature of the ocean currents flowing under the ice shelf. Over several days they tossed 6,000 kilograms of hard snow, one block at a time, into a canvas-sided tank the size of a large hot tub. They melted the snow and heated the water, then used it to make a hole as wide as a dinner plate 250 meters down through the shelf. Scambos lowered a string of sensors through this hole into the ocean water below. For the next year or two this sensor station, powered in part by solar panels on a small steel tower, would measure the water temperature, salinity and currents.

Initial readings showed that warm, dense water was indeed flowing under the shelf. At two degrees above freezing, it should be "enough to melt many meters of ice over the course of a year," Scambos said. But the ice wasn't feeling the heat. A layer of cold water sat up against the shelf's underside. Because that water came from the melting of glacial ice (which itself comes from snow), it contained little salt, so it was buoyant, hugging the bottom of the shelf and shielding it from the warmer, saltier water below.

ERIN PETTIT pulls an ice-penetrating radar (*above*) that can peer down into the ice shelf. She walked for many kilometers beyond base camp, where tents were protected from constant wind by walls made of handsawed snow blocks (*right*).

By the end of the expedition Pettit's team had encountered a series of revelations that defied previous views of the ice shelf. First, its underside was eroded with deep trenches, and the slopes of those trenches were organized into stair-stepped terraces. Second, the ice didn't appear to be thinning at the points Wild measured, which disagreed with satellite surveys. Finally, the underside of the shelf didn't seem to be feeling heat from the deep ocean, because it was insulated by a layer of cold, buoyant water. This set of findings was difficult to explain, but another research expedition, operating not far away, would help make sense of the surprises.

Douglas Fox

EIGHT KILOMETERS SOUTHEAST OF PETTIT'S CAMP, THE OTHER GROUP of scientists was getting a first look at the ice shelf's grounding line—the long contour of ground where ice lifts off the land and floats on the sea. In this hidden place, scientists believed the underside of the ice was melting most quickly.

On January 11, 2020, researchers at the camp lowered a black-and-yellow cylindrical vehicle, as wide as two hands and 3.5 meters long, by cable into a narrow hole in the ice. Engineers led by Britney Schmidt, a planetary and polar scientist now at Cornell University (then at the Georgia Institute of Technology), had spent eight years developing this remotely operated vehicle, called Icefin. They had driven it under sea ice more than a meter thick and under the edges of two small ice shelves, where it could be winched out by cable if it got stuck. But they had never lowered this precious object through such a massive slab.

Schmidt sees Icefin as a prototype of a probe that will one day explore vast bodies of water in the outer solar system, hidden underneath 10 or 20 kilometers of ice on Jupiter's and Saturn's moons. In Antarctica, Icefin would measure the ocean temperatures, currents and rates of melting under the ice. Perhaps more important, its video cameras and sonar would allow the researchers to visually explore this remote environment. Schmidt wasn't looking to validate any of Pettit's observations per se, but the two researchers were working relatively close by, on the same ice shelf, so serendipity could play a role.

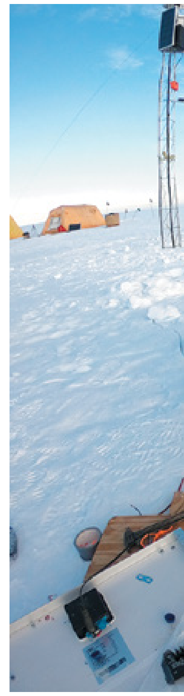
After descending through the 600 meters of ice, the vehicle emerged into a layer of ocean water only 50 meters deep. Schmidt, sitting in a nearby tent, steered Icefin with her thumbs on the controller of a PlayStation 4 console. The glassy ceiling of the ice's underside scrolled past on her video monitor as Icefin glided along, sending video up its fiber-optic tether. For eight hours Schmidt guided the vehicle as far as two kilometers from the borehole, into narrow spaces where less than a meter of water separated the ice above from the gravelly, gray-brown seafloor below. This was newly exposed seafloor; the thinning ice had pulled away from it only a few days or weeks before. An occasional fish or shrimp drifted by.

In most places, the currents were sluggish, and close to the ice the water was stratified. As the vehicle approached the grounding line, the water near the ice was at most one degree Celsius above freezing, even though warmer water lay only a few meters away. Icefin's measurements suggested that the underside of the ice was melting at a modest rate of about two meters a year. In some places, meltwater had refrozen onto the bottom of the glacier, revealing a distinct layer of crystal-clear ice, several centimeters thick. Satellite observations had shown this region rapidly thinning, so the findings were at odds with the team's expectations, says Keith Nicholls, an oceanographer at the British Antarctic Survey, who co-led the research at the camp. The overall lack of melting was puzzling, he said: "Extraordinary, really."

As Icefin swam around, it occasionally encountered a clue that would help explain not only these unanticipated observations but also what Pettit's team had found. Cruising slowly along the shelf's fairly flat underside, Icefin came across a vertical wall cut up into the ice—a stair-stepped terrace like Pettit had seen in her radar traces. And the ice on the terrace walls seemed to be melting far more quickly than the surrounding horizontal underside. In the video, there were blurry ripples in the water, where Icefin's spotlight refracted through gushing eddies of saltwater and freshwater swirling together. Icefin also frequently found dark cracks gaping in the ice—basal crevasses as wide as 100 meters. Schmidt steered Icefin up into several of the crevasses, and there again, she found the water swirling and blurry, suggesting the ice may have been melting quickly.

At the December 2021 American Geophysical Union (AGU) meeting in New Orleans, Schmidt's team presented a careful analysis of Icefin's data, confirming that the vertical ice surfaces are playing a pivotal role in the demise of the Thwaites Ice Shelf. Peter Washam, a research scientist at Cornell, reported that the terrace walls were melting five times more quickly than horizontal ice surfaces, losing 10 or more meters of ice a year. The crevasse walls were melting even more quickly—up to 10 times as fast, los-

Douglas Fox



ing 20 meters of ice a year. Washam noted that the water currents became turbulent as they encountered these steep surfaces, and this brought water into contact with the ice in ways that more efficiently melted it.

The vertical steps may originate from subtle ups and downs present on the ice's underside when it first pulls up from the bed along the grounding line. The ice might fracture and melt more quickly in these uneven spots, steepening the slope—which increases the melt rate, causing the slope to steepen even more, until it forms a terrace wall that is nearly vertical. As ice melts from these vertical surfaces, the terrace walls migrate horizontally, Scambos says. A basal crevasse that is 10 meters across might widen to 30 or even 50 meters within a year. The melting of the Thwaites Ice Shelf's underside isn't a uniform process; it is highly localized, directed by the topography interacting with currents.

If most of the melt is happening on the vertical ice faces, that could help explain why Wild saw no signs of thinning in many of the places he measured. After returning home in 2020, Pettit plotted Wild's points on her radar survey lines showing the terrace walls. In each case, Wild's measurements fell some distance from the closest wall, in a spot where the ice base was horizontal and so maybe not melting much. This isn't unusual, Pettit says, because the walls are spaced far enough apart that Wild was unlikely to hit one by chance. The instrument station that Scambos left behind also seems to be located some distance from the nearest wall; it, too, has shown very little ice thinning.

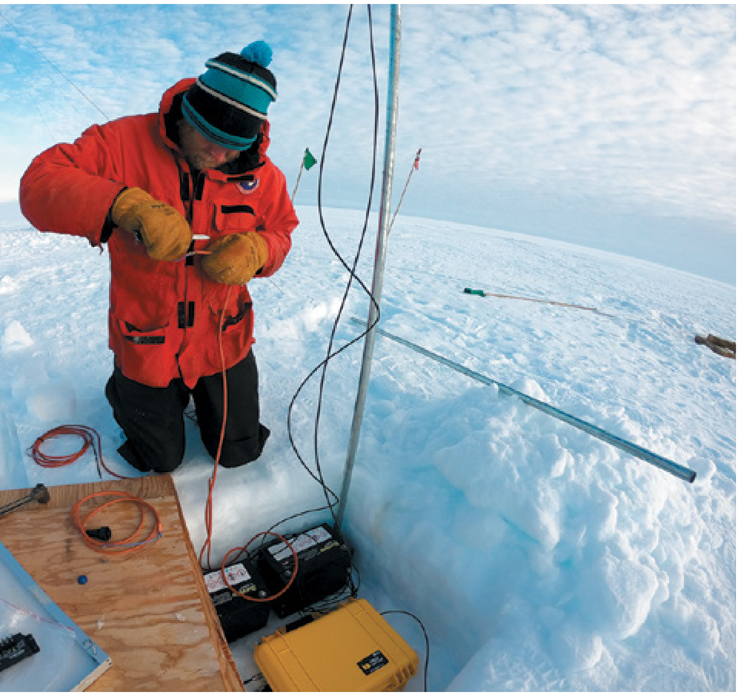
If the vertical walls are melting quickly, they should also be migrating horizontally across the ice base, Pettit says. At some point, one of those vertical faces will sweep past Scambos's instrument station, "and we will see a huge amount of melt in a short time," she says—perhaps eight meters in a week. "If we see that, it would be supercool."

Schmidt's observations may also explain another feature of the terraced trenches Pettit saw near camp. After Pettit returned home, she examined her radar traces and noticed something peculiar: in the highest segment of a trench, she often saw a stack of inverted U-shaped radar reflections—the classic signature of a crevasse penetrating up into the ceiling. This might occur because the thinner ice over a trench sags like a flimsy bridge; as the ice flexes downward, its bulging belly cracks open. This newly formed basal crevasse may pull in warmer water from below. That would cause the walls of the crevasse to melt and migrate outward, widening until its ceiling is broad enough that it also sags and cracks open—a repeating cycle that could drive cracks ever farther into the ice above.

The massive terraced trenches may have started out as individual basal crevasses, like the ones Schmidt saw eight kilometers upstream at the grounding zone. When Elisabeth Clyne, then a graduate student at Pennsylvania State University, examined radar traces from around the grounding zone, she saw signs that as crevasses moved farther out toward the sea, at roughly 600 meters a year, they were already starting to grow wider and taller through cycles of melting, sagging and cracking. She reported her analysis at the 2021 AGU meeting in New Orleans. Pettit suspects that these trenches may eventually penetrate all the way up through the shelf or at least cut far enough up through the ice that the shelf becomes prone to breaking from other stresses. This process could splinter the shelf into an unsteady mass of giant, shifting shards that will no longer stabilize one of Antarctica's largest glaciers.

ALTHOUGH THWAITES'S WESTERN ICE TONGUE LOST 80 PERCENT OF ITS area in the past 25 years, the eastern shelf shrunk only about 15 percent. Its seaward snout remains pressed against the undersea mountain ridge, which crests roughly 400 meters underneath the ocean's surface. The pressure from this "pinning point" holds the ice together, but the status quo may not last much longer.

Douglas Fox



Douglas Fox

CHRISTIAN WILD prepares a high-precision radar (*left*) to measure ice-shelf thickness to within a few millimeters. Martin Truffer sets up an instrument station (*above*) that would record the shelf's advancement and upheaval for two years after researchers left Thwaites.

In February 2022 Wild published an analysis of satellite measurements showing that the front face of the ice in contact with the underwater mountain ridge is thinning by 30 centimeters a year. At that rate, it will lift off the top of the mountains in the next 10 years. Wild expects that when this happens, the eastern ice shelf will rapidly "disaggregate" into a flotilla of icebergs. But it may meet its end even sooner. If focused terrace melting is driving cracks upward through the ice, that could amplify the mechanical stresses that are already tearing at the shelf.

Massive splintering is already happening just upstream of the mountain ridge. Over the past decade the ice there has fragmented into a logjam of long shards held together only by pressure and friction. A series of satellite images, stitched into an animation by Andrew Fleming of the British Antarctic Survey, shows that these shards are sliding past one another with increasing ease. As a result, the splintering shelf is starting to deform and flow around the mountain ridge more quickly and in new directions, like a river that parts as it flows around a boulder. The mountain—once a stabilizing buttress—is now acting as a wedge, sending several "dagger" rifts surging back toward land. These are the same rifts that we saw via satellite just before we left for Antarctica in 2019.

"The thing is falling apart," says Karen Alley, a glaciologist at the University of Manitoba in Winnipeg, who published an analysis of these ice-flow patterns in November 2021. Even if the ice disconnects from the mountain ridge more slowly than expected, another scenario could doom the shelf. Those dagger rifts could keep lengthening until they intersect with the rising trenches advancing seaward from shore. This intersection of structural defects could lead to a shattering of the entire shelf.

In every scenario, the eastern ice shelf will meet a fate similar to the western ice tongue: its constituent shards will disconnect and drift away. Once that happens the eastern trunk of the Thwaites Glacier will break away from its pinning point, and the western trunk could also speed up. "This whole thing is going to go much faster once the ice [shelf] is all cleared out," Scambos predicts.

PETTIT'S TEAM LEFT THWAITES IN LATE JANUARY 2020, BUT THEY are still monitoring the shelf's health using solar-powered instruments they lowered into the ocean through holes drilled through the ice. In January 2022 Scambos and Wild returned to our camp site for a few chaotic days to retrieve the data. Antenna and solar towers that once rose seven meters above the ice were mostly buried in hard, icy snow. Scambos, Wild and two other workers used ice-penetrating radar to find the buried instruments. They then chain-sawed narrow pits six meters down into the ice to retrieve the treasured data cards.

In hopes of getting another year of data out of his instruments, Scambos reinforced the steel towers that had been bent like paper clips and reset the modems that had been fried by static discharge during windstorms. Sensors on the towers had detected winds up to 250 kilometers per hour—nearly Category 5 hurricane speeds and twice what Scambos expected.

GPS units from those stations show that in the two and a half years since they were installed, the ice shelf's seaward movement increased from 620 meters a year to 980 meters a year. As Scambos and Wild gazed down from their Twin Otter plane this past January, they spotted several new tears in the shelf—three kilometers long and several hundred meters wide—where it lifts off the seafloor. Ragged cliffs of ice tilted 50 meters up into the air, exposing deep layers that had not seen daylight for thousands of years. "I think it's losing contact with everything that used to be bracing it," Scambos says. Not only is the ice shelf separating from its pinning point. As it speeds up, it is also stretching and tearing away from the glacier upstream.

The team was so alarmed that Pettit and Wild decided they will return this December to install a new instrument station: "BOB," short for Breakup Observer. They hope BOB will survive long enough to record the final throes of the ice shelf as it fractures into shards. It might not take long.

Scambos speculates that as Pettit and Wild camp on the ice shelf in December, they may wake up one morning to find themselves on a free-floating iceberg. "As long as they're not near one of the rifts, they're not even going to know" at first, he says. Any sounds or vibrations from a crevasse breaching the surface from below might be muffled. Subtle clues will gradually alert them. As the iceberg slowly rotates, their handheld GPS will seem to guide them in the wrong direction, and the sun might also move the wrong way. "You're on this giant white lily pad," Scambos says, "and your only reference is that you're used to having the sun in a certain place at a certain time of day." SA

FROM OUR ARCHIVES

Is Antarctica Collapsing? Richard B. Alley; February 2019.

scientificamerican.com/magazine/sa

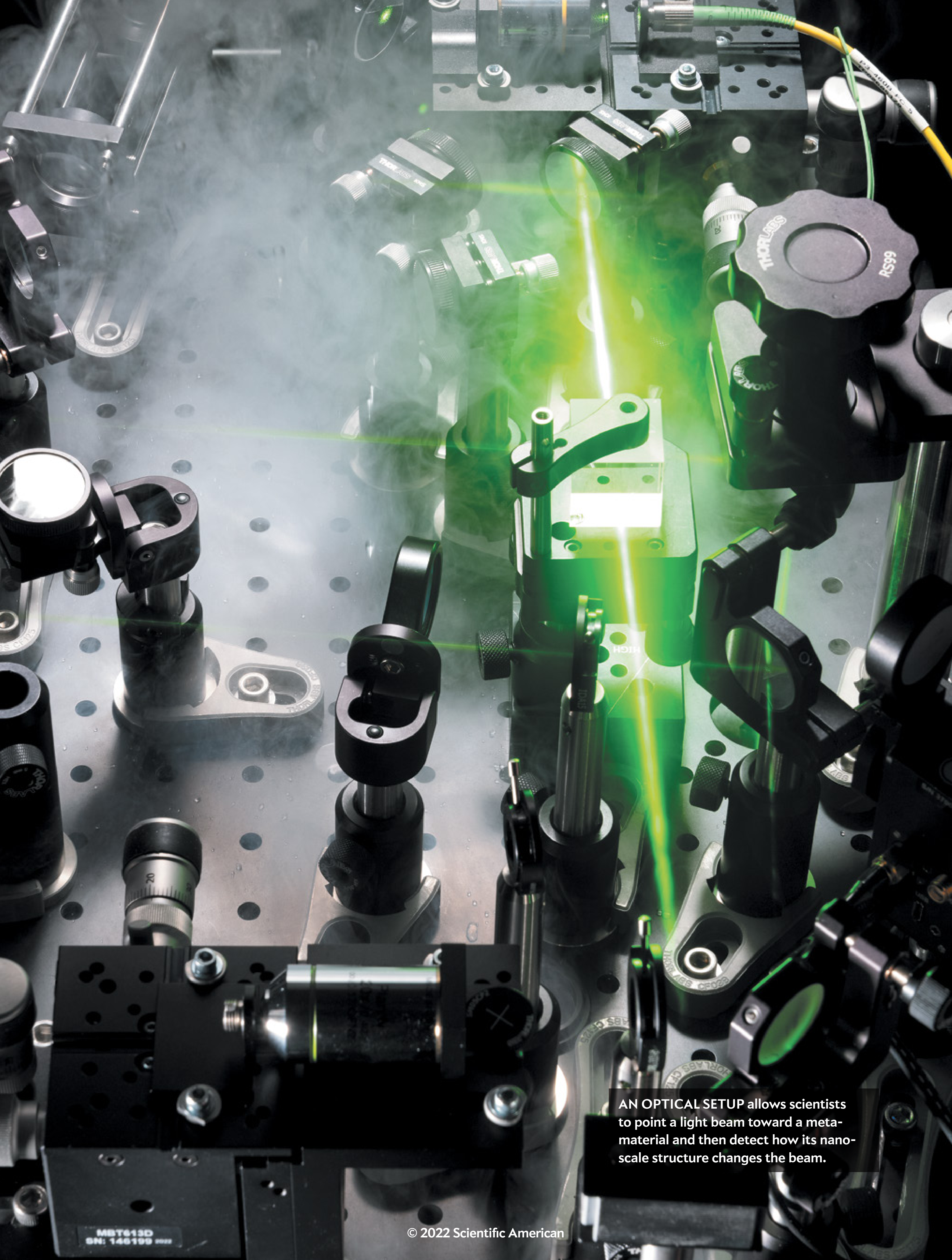
MATERIALS SCIENCE

Tricking Light

Newly invented metamaterials can modify waves, creating optical illusions and useful technologies

By Andrea Alù

Photographs by Craig Cutler



AN OPTICAL SETUP allows scientists to point a light beam toward a metamaterial and then detect how its nanoscale structure changes the beam.

Andrea Alù is a physicist and engineer at the City University of New York (CUNY) Graduate Center, where he directs the Photonics Initiative at the CUNY Advanced Science Research Center.

WE ARE SURROUNDED BY WAVES. TINY VIBRATIONAL WAVES TRANSPORT SOUND TO our ears. Light waves stimulate the retinas of our eyes. Electromagnetic waves bring radio, television and endless streaming content to our devices. Remarkably, all these different waves are governed largely by the same fundamental physical principles. And in the past few years there has been a revolution in our ability to control these waves using materials, engineered at the nanoscale, known as metamaterials.

The Greek prefix *meta* means "beyond." These engineered materials let us move beyond the traditional ways in which waves and matter interact, creating technologies where light and sound appear to disobey conventional rules. The marquee example of this new style of materials is the "invisibility cloak"—a metamaterial coating that can hide an object in plain sight. Several research teams around the world, including mine, have designed and produced metamaterial coatings that can redirect light waves that hit them, effectively preventing light from bouncing off the object and reaching our eyes and even from leaving shadows. Although these inventions have limitations—they aren't quite the Harry Potter–style invisibility cloaks that many people imagine—they nonetheless interact with light in a way that seems like magic.

Cloaks are just one example of metamaterial technology. Other metamaterials allow light to travel one way but not the opposite—a valuable tool for communication and detection of objects—and to break symmetries of geometry and time. With modern nanofabrication tools and a better understanding of how light and matter interact, we can now structure metasurfaces to produce any pattern, color and optical feature we can think of.

BENDING AND TWISTING LIGHT

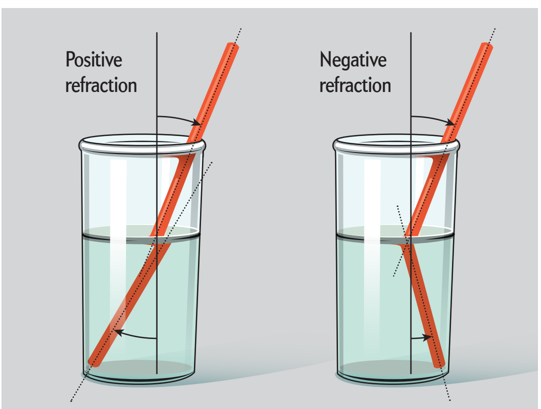
FOR CENTURIES scientists have strived to control the properties of light and sound as they interact with our sensory systems. An early success in this quest was the invention of stained glass: ancient Romans and Egyptians learned how to melt metallic salts into glass to tint it. The tiny metal nanoparticles dispersed in the glass absorb specific wavelengths and let others through, creating bright colors in masterpieces that we still admire today. In the 17th century Isaac Newton and Robert Hooke recognized that the hue and iridescence of some animals are created by nanoscale patterns on the surface of their body parts—another example of how nanostructured materials can create surprising optical effects.

Human eyes are excellent at detecting two fundamental properties of light: its intensity (brightness) and its wavelength—that is, its color. A third important property of light is its polarization, which describes the trajectory that light's electromagnetic fields trace in space over time. Although humans cannot distinguish one polarization from another with our eyes, several animal species have polarization sensitivity, allowing them to see more, better orient themselves in their surroundings and signal to other creatures.

In the late 19th century, a few years after James Clerk Maxwell's discovery of the equations of electromagnetism, Jagadish Chandra Bose built the first examples of what we could call a metamaterial. By manually twisting jute fibers and arranging them in regular arrays, he demonstrated that linearly polarized electromagnetic waves—light whose electric and magnetic fields oscillate along straight lines—rotate their polarization as they propagate through and interact with the jute structures. Bose's twisted jute showed that it was possible to engineer an artificial material to control light in unprecedented ways.

The modern era of metamaterials can be traced back to 2000, when physicists David R. Smith of Duke University, the late Sheldon Schultz of the University of California, San Diego, and their colleagues created an engineered material unlike any seen before—a material with a *negative* index of refraction. When a beam of light travels from one medium to another—from air to glass, say—its speed changes, causing the beam to bend, or "refract." The difference in index of refraction between the two materials defines the angle of that bending.

Refraction phenomena are the basis of most modern optical devices, including lenses and displays, and explain why a straw in a glass of water looks broken. For all known natural materials, the index of refraction is positive, meaning that light always bends on the same side of the interface, with a larger or smaller angle from the interface as a function of the change in index. Light entering a medium with a negative index of refraction, on the contrary, would bend backward, creating unexpected optical effects, such as a straw appearing to lean the wrong way. Scientists long assumed that it was impossible to find or create a material supporting negative refraction, and some argued that it would violate fundamental physical principles. When Schultz, Smith and their colleagues combined tiny copper rings and wires on stacked circuit-board substrates, however, they demonstrated that a microwave beam passing through this engineered material undergoes negative refraction. This striking advance showed that metamaterials can yield a much wider set of refractive indexes than nature offers, opening the door to totally new technological possibilities. Since then, researchers have created negative-index materials for a wide range of frequencies, including for visible light.



CLOAKING TECHNOLOGIES

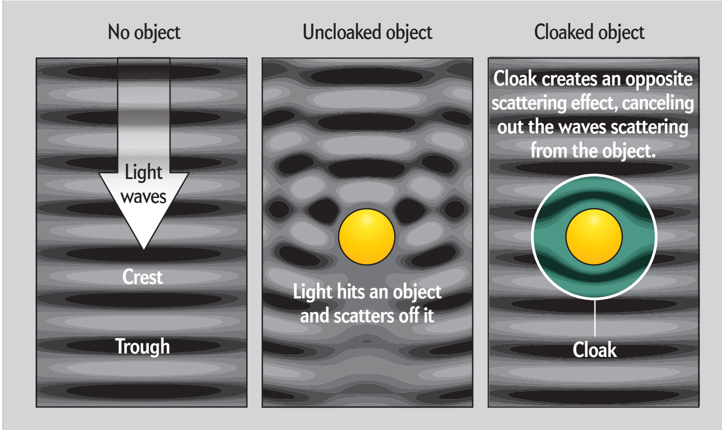
AFTER THIS INITIAL BREAKTHROUGH, a great deal of metamaterial research focused on cloaking. Around 15 years ago, while I was working with Nader Engheta of the University of Pennsylvania, we designed a metamaterial shell that would make an object undetectable by causing the light waves bouncing off the shell to cancel out the light waves scattered from the cloaked object. No matter which direction it came from, a wave that hit the structure would be redirected by the cloak in a way that canceled the wave scattered by the object itself. As a result, the cloaked object would be impossible to detect via external illumination: from an electromagnetic point of view, it would appear not to exist.

Around the same time, John B. Pendry of Imperial College London and Ulf Leonhardt, now at the Weizmann Institute of Science in Rehovot, Israel, proposed other interesting ways to use metamaterials to cloak objects. And within a few years various experimental demonstrations turned these proposals into reality. My group, for instance, produced a three-dimensional cloak that can drastically reduce the amount of radio waves that scatter off of a cylinder, making it difficult to detect via radar. Existing stealth technologies can hide objects from radar by absorbing the impinging waves, but metamaterial cloaks do much better because they don't just suppress the reflected waves—they reroute the incoming waves to eliminate scattering and shadows, making the cloaked object undetectable. We and other groups have extended cloaking to acoustic (sound) waves, creating objects that can't be detected by sonar devices. Other scientists have even made cloaks for thermal and seismic waves.

There is, however, a long way to go from these devices to invisibility cloaks like those pictured in movies, which allow the multiwavelength background behind an object to shine through. Our real-life cloaks are limited to either small sizes or narrow wavelengths of operation. The underlying challenge is the competition against the principle of causality: no information can travel faster than the speed of light

Cloaking

One of the biggest early successes of metamaterials is the invention of a coating that hides an object from view. Under normal circumstances, as light hits an object, its waves are disturbed and scattered, revealing the object's presence (*center*). A metamaterial cloak, however, causes the light bouncing off it to perfectly cancel the light reflected from the object underneath it, producing undisturbed light waves that conceal the object's presence (*right*).



in free space. It is impossible to fully restore the background electromagnetic fields as if they were traveling through the object without slowing them down.

Based on these principles, my group has demonstrated that we cannot *completely* suppress scattering from an object at more than a single wavelength (a single color of light) using a passive metamaterial coating. Even if we induce only partial transparency, we face a severe trade-off between how big the cloaked object can be and how many colors of light we can cloak it for. Cloaking a large object at visible wavelengths remains far-fetched, but we can use metamaterial cloaks for smaller objects and longer wavelengths, with exciting opportunities for radar, wireless communications and high-fidelity sensors that don't perturb their surroundings as they are operated. Cloaks for other kinds of waves, such as sound, have fewer limitations because these waves travel at much slower speeds.

SPATIAL SYMMETRIES

A PARTICULARLY POWERFUL TOOL for designing and applying metamaterials for various purposes is the concept of symmetry. Symmetries describe aspects of an object that do not change when it is flipped, rotated or otherwise transformed. They play a fundamental role in all natural phenomena. According to a 1915 theorem by mathematician Emmy Noether, any symmetry in a physical system leads to a conservation law. One example is the connection between temporal symmetry and energy conservation: if a physical system is described by laws that do not explicitly depend on time, its total energy must be preserved. Similarly, systems obeying spatial symmetries, such as periodic crystals that remain the same under translations or rotations, preserve some properties of light, such as its polarization. By breaking symmetries in controlled ways, we can design metamaterials to overcome and locally tailor these conservation laws, enabling novel forms of light control and transformation.

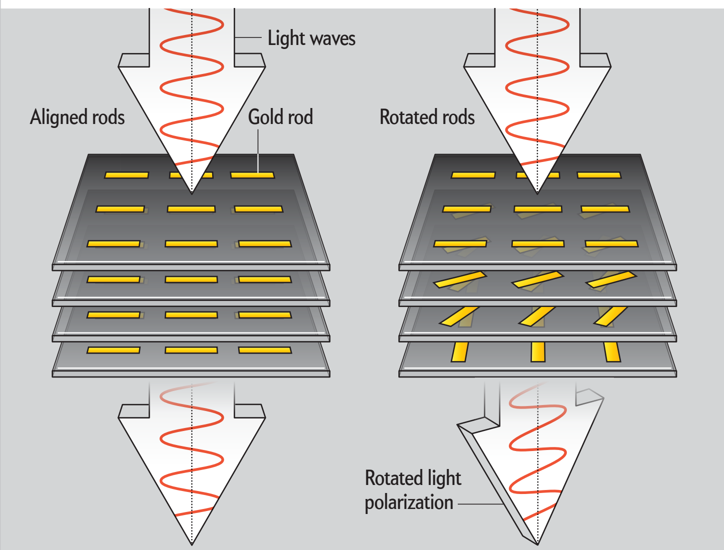
As an example of the powerful role of symmetries for metamaterial design, my group has engineered an optical metamaterial that can efficiently rotate the polarization of light that travels through it—in some ways, it is a nanoscale version of Bose's twisted jute arrangement. The material is made of multiple thin layers of glass, each one embedded with rows of gold rods, tens of nanometers long. First, we create one layer of nanorods all oriented in a certain direction over the glass. Then we stack a second layer, which looks identical to the first, except that we rotate all the rods at a specific angle. The next layer is adorned by nanorods further rotated by this same angle, and so on. Overall, the stack is only about a micron thick, yet it features a specific degree of broken spatial symmetry compared with natural periodic crystals, where molecules are all lined up in straight rows. As light passes through this thin metamaterial, it interacts with the gold nanorods and is slowed down by electron oscillations at their surface. The emerging light-matter interactions are controlled by the twisted symmetry of the crystal lattice, enabling a large rotation of the incoming light polarization over a broad range of wavelengths. This form of polarization control can benefit many technologies, such as liquid-crystal displays and sensing tools used in the pharmaceutical industry, which rely on polarization rotation that typically emerges much less efficiently in natural materials.

Underlying rotational symmetries also play a crucial role in governing other metamaterial responses. Pablo Jarillo-Herrero's group at the Massachusetts Institute of Technology recently showed that two closely spaced layers of graphene—just a single layer of atoms each—carefully rotated with respect to one another by a precise angle result in the striking emergence of superconductivity. This feature, which the two layers individually do not possess, allows electrons to flow along the material with zero resistance, all because of the broken symmetry induced by the twist. For a specific rotation angle, the emerging interactions between the neighboring atoms in the two layers define a totally new electronic response.

Inspired by this demonstration, in 2020 my group showed that a somewhat analogous phenomenon can occur not for electrons but for light. We used a stack of two thin layers of molybdenum trioxide (MoO_3) and

Broken Symmetry

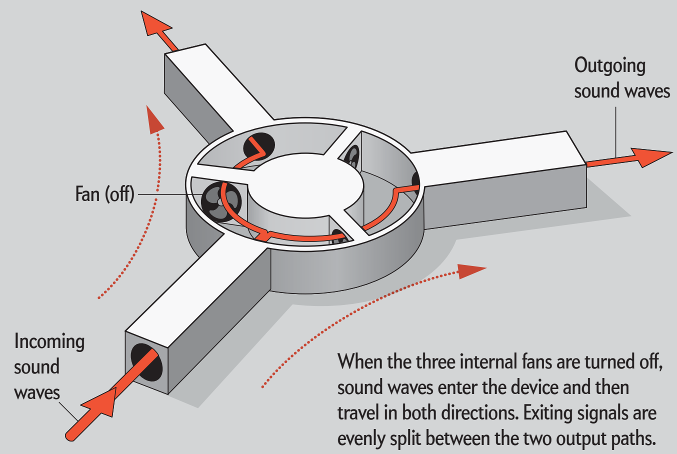
One way to alter how waves travel through a material is by breaking its usual symmetry. The author's group, for instance, created a metamaterial by layering sheets of glass with tiny gold nanorods embedded within them. In each layer, the rods are rotated by a specific angle, destroying the perfect symmetry between layers. The effect is that the material forces the polarization of light waves traveling through it to rotate—a useful trick for many modern technologies.



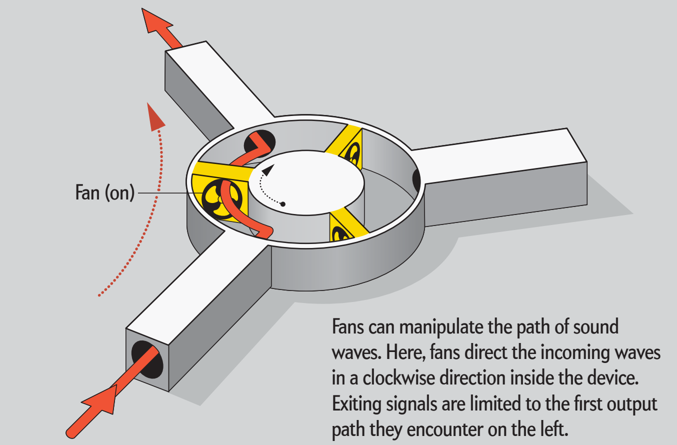
A METAMATERIAL undergoes testing in a chamber that enables very precise measurements of radio and millimeter-wavelength light.

One-Way Sound

Another way to play with broken symmetry is with a device the author's group created in which sound can travel in only one direction. The structure consists of a circular aluminum cavity in which small fans spin air. Because of the Doppler effect, the cavity resonates at different frequencies for clockwise-traveling sound waves than for waves going the other way. The resulting interference lets sound through in just one direction.



When the three internal fans are turned off, sound waves enter the device and then travel in both directions. Exiting signals are evenly split between the two output paths.



Fans can manipulate the path of sound waves. Here, fans direct the incoming waves in a clockwise direction inside the device. Exiting signals are limited to the first output path they encounter on the left.

Ultimately we can connect many of these devices to form a hexagonal lattice that supports robust one-way sound transport on its boundary.

rotated one with respect to the other. Individually each layer is a periodic crystal lattice, in which the underlying molecules are arranged in a repeating pattern. When light enters this material, it can excite the molecules, causing them to vibrate. Certain wavelengths of light, when polarized in a direction aligned with the molecules, prompt strong lattice vibrations—a phenomenon called a phonon resonance. Yet light with the same wavelength and perpendicular polarization produces a much weaker material response because it does not drive these vibrations. We can take advantage of this strong asymmetry in the optical response by rotating one layer with respect to the second one. The twist angle once again controls and modifies the optical response of the bilayer in dramatic ways, making it very different from that of a single layer.

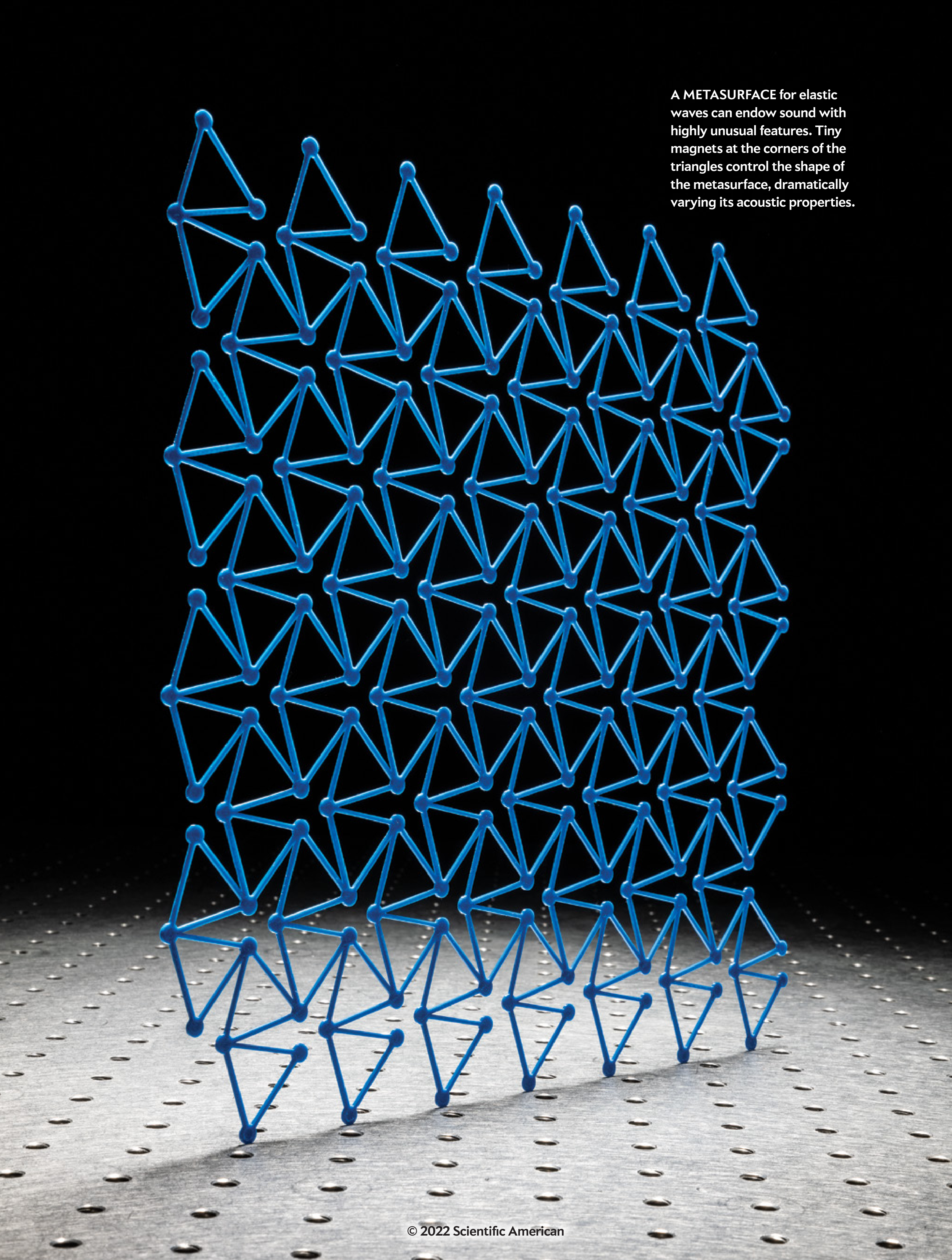
For example, light emitted by a molecule placed on the surface of a conventional material such as glass or silver flows outward in circular ripples, as when a stone hits the surface of a pond. But when our two MoO_3 layers are stacked on top of each other, changing the twist angle can drastically alter the optical response. For a specific twist angle between the crystal lattices, light is forced to travel in just one specific direction, without expanding in circular ripples—the analogue of superconductivity for photons. This phenomenon opens the possibility of creating nanoscale images beyond the resolution limits of conventional optical systems because it can transport the subwavelength details of an image without distortion, efficiently guiding light beyond the limits imposed by diffraction. Light in these materials is so strongly linked to material vibrations that the two form a single quasiparticle—a polariton—in which light and matter are strongly intertwined, offering an exciting platform for quantum technologies.

SYMMETRIES IN TIME

THE ROLE OF SYMMETRY in metamaterials is not limited to spatial symmetries, such as the kind broken by geometric rotations. Things get even more interesting when we experiment with breaking time-reversal symmetry.

The equations that govern wave phenomena are typically reversible in time: if a wave can travel from point A to point B, it can also travel back from B to A with the same features. Time-reversal symmetry explains the common expectation that if we can hear or see someone, they can also hear or see us. Breaking this symmetry in wave transmission—known as reciprocity—can be important for many applications. *Nonreciprocal* transmission of radio waves, for instance, can enable more efficient wireless communications in which signals can be transmitted and received at the same time without interference, and it can prevent contamination by the reflection of signals you send out. Nonreciprocity for light can protect sensitive laser-beam sources from unwanted reflections and provides the same benefit in radar and lidar technologies.

An established way to break this fundamental symmetry exploits magnetic phenomena. When a ferrite—



A METASURFACE for elastic waves can endow sound with highly unusual features. Tiny magnets at the corners of the triangles control the shape of the metasurface, dramatically varying its acoustic properties.

a nonmetallic material with magnetic properties—is subject to a constant magnetic field, its molecules sustain tiny circulating currents that rotate with a handedness determined by the magnetic field orientation. In turn, these microscopic currents induce a phenomenon called Zeeman splitting: light waves with right-handed circular polarization (an electric field that rotates clockwise) interact with these molecules with a different energy than left-handed (counterclockwise) waves. The difference in energy is proportional to the applied magnetic field. When a linearly polarized wave travels through a magnetized ferrite, the overall effect is to rotate the polarization, in some ways similar to the metamaterials discussed earlier. The fundamental difference is that here the handedness of the polarization rotation is determined by the external magnetic bias, not by the broken symmetry in the metamaterial constituents. Hence, in these magnetized materials, light's polarization rotation has the same handedness when it's traveling in one direction as it does when it's moving in the opposite direction—a feature that violates reciprocity. Time-reversal symmetry is now broken.

We can exploit this phenomenon to engineer devices that allow waves to propagate in only one direction. Yet few natural materials possess the desired magnetic properties to achieve this effect, and those that do can be difficult to integrate into modern devices and technologies based on silicon. Over the past few years the metamaterials community has been working hard to create more efficient ways to break wave reciprocity without magnetic materials.

My group has shown that we can replace the tiny circulating currents in a magnetized ferrite with mechanically rotating elements in a metamaterial. We achieved this effect in a single compact acoustic device by using small computer fans spinning air inside a circular aluminum cavity, creating a first-of-its-kind nonreciprocal device for sound. When we turn on the fans, the frequencies at which the cavity resonates are different for counterrotating sound waves, similar to how Zeeman splitting changes the energy of light's interactions in a ferrite. As a result, a sound wave in this rotating cavity experiences a very different interaction depending on whether it travels clockwise or counterclockwise inside it. We can then route sound waves nonreciprocally—one-way only—through the device. Remarkably, the airflow speed necessary to create this effect is hundreds of times slower than the speed of the sound waves, making this technology quite simple to develop. Such compact nonreciprocal devices can then form the basis of a metamaterial, made by connecting these elements in a lattice. These engineered crystal lattices transport sound in highly unusual, nonreciprocal ways, reminiscent of how electrons travel with unique features in topological insulators.

Can we use a similar trick for light? In 2018 Tal Carmon's group at Tel Aviv University demonstrated an analogous effect by spinning the read-head of a hard-disk drive coupled to an optical fiber at kilohertz frequencies, demonstrating nonreciprocal transmission of light through it. The researchers' setup showed that mechanically rotating elements can be used to force light to travel through a device in one direction only. An arguably more practical route is to use metamaterials made of time-varying constituents that are switched on and off with specific patterns in space, mimicking rotation. Based on these principles, my group has created several technologies that operate efficiently as nonreciprocal devices. Their small footprints allow us to easily integrate them into larger electronic systems.

We have also extended these techniques to thermal emission, the radiation of light driven by heat. All hot bodies emit light, and a universal principle known as Kirchhoff's law of thermal radiation states that reciprocal materials in equilibrium must absorb and emit thermal radiation at the same rate. This symmetry introduces several limitations for device designs for thermal energy management and for energy-harvesting devices such as solar cells. By employing design principles similar to the ones described earlier to break light reciprocity, we are envisioning systems that do not obey the symmetry between absorption and emission. We can structure metamaterials to efficiently absorb heat without needing to reemit a portion of the absorbed energy toward the source, as a normal material would, enhancing the amount of energy we can harvest. Applied to static mechanics, analogous principles have also allowed us to create a 3-D-printed object that asymmetrically transmits an applied static mechanical force—a kind of one-way glove that can apply pressure without feeling the back action.

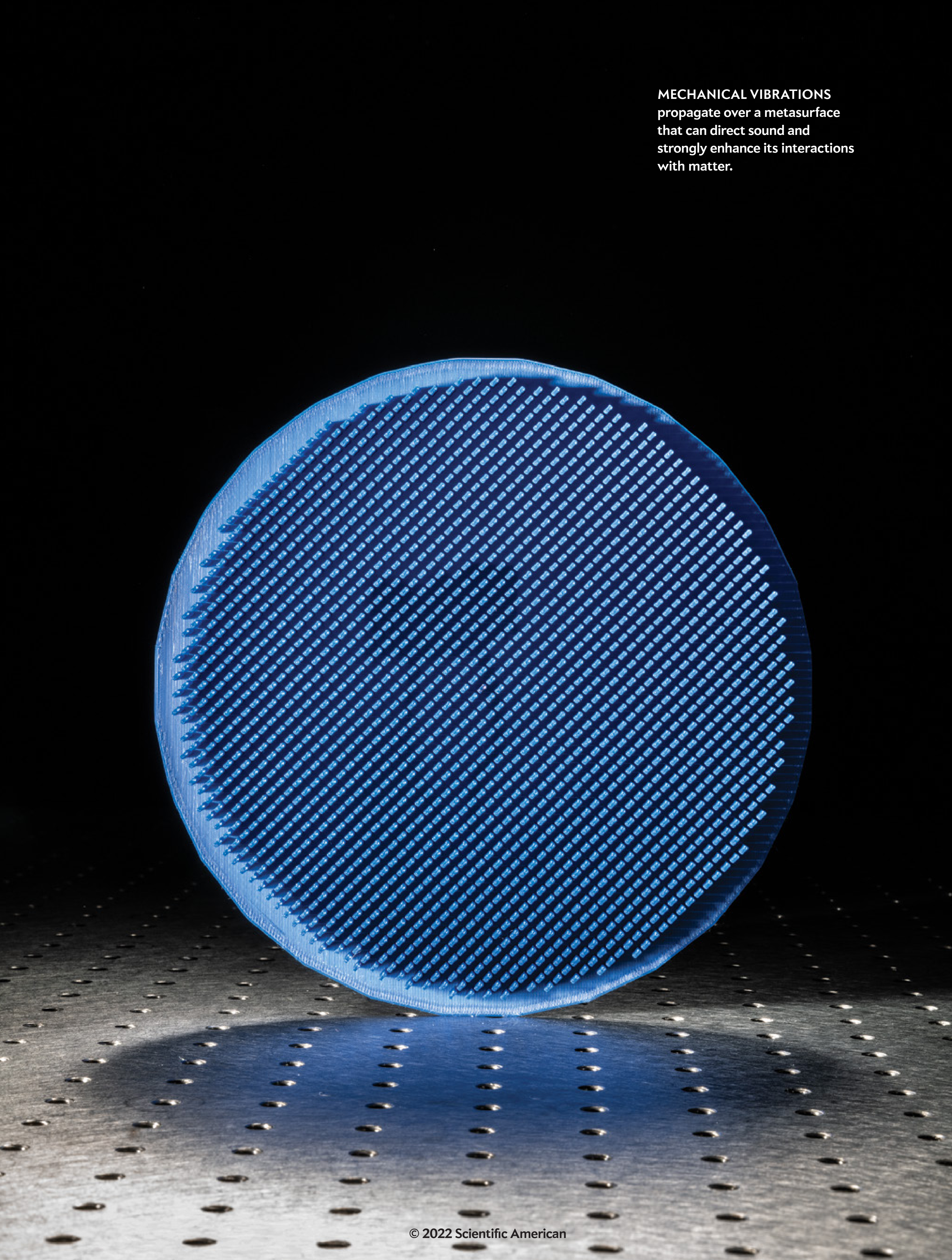
MANY MORE WONDERS

THE OPPORTUNITIES OFFERED by metamaterials and broken symmetries to manipulate and control waves do not end here. Scientists have been discovering new ways to trick light and sound—for instance, by combining broken geometric symmetries and temporal symmetries in novel ways. Metamaterials can be featured on the walls and windows of smart buildings to control and route electromagnetic waves at will. Nanostructured metasurfaces can shrink bulky optical setups into devices thinner than a human hair, enhancing imaging, sensing and energy-harvesting technologies. Acoustic and mechanical metamaterials can route and control sound with an unprecedented degree of control. We expect many more wonders, given the enormous opportunities that modern nanofabrication techniques, our improved understanding of light-matter interactions, and sophisticated materials science and engineering present us. SA

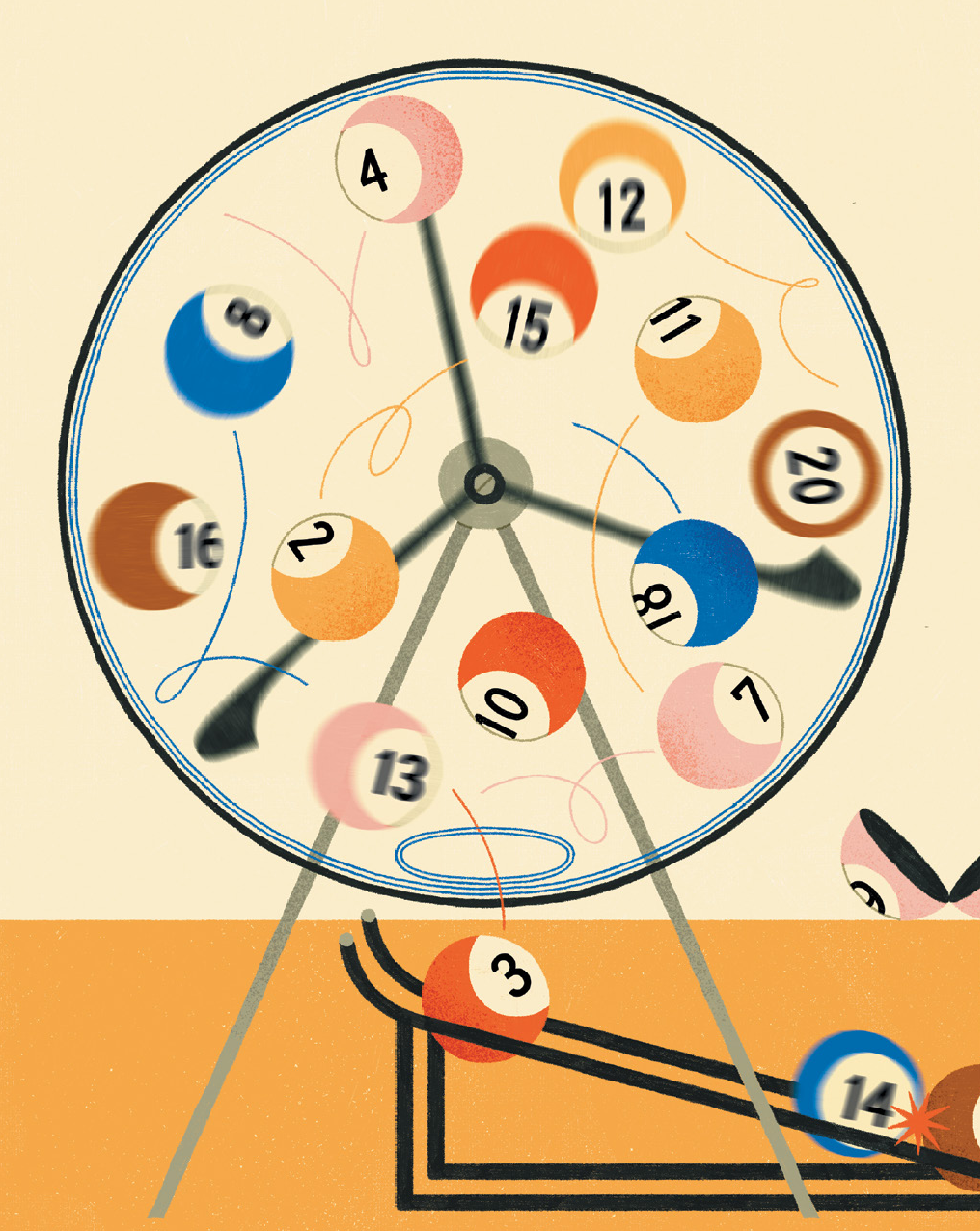
FROM OUR ARCHIVES

The Quest for the Superlens. John B. Pendry and David R. Smith; July 2006.

scientificamerican.com/magazine/sa



MECHANICAL VIBRATIONS propagate over a metasurface that can direct sound and strongly enhance its interactions with matter.



MATHEMATICS

A More Perfect Algorithm

Computing citizens' assemblies more fairly empowers democracy

By Ariel Procaccia

Illustration by Montse Galbany

Ariel Procaccia is Gordon McKay Professor of Computer Science at Harvard University. He is an expert in algorithms and artificial intelligence and is especially interested in questions of societal importance.

IN 1983 THE EIGHTH AMENDMENT TO THE IRISH CONSTITUTION ENSHRINED AN ABORTION BAN that had prevailed in the nation for more than a century. Public opinion on the issue shifted in the new millennium, however, and by 2016 it was clear that a real debate could no longer be avoided. But even relatively progressive politicians had long steered clear of the controversy rather than risk alienating voters. Who would be trustworthy and persuasive enough to break the deadlock?

The answer was a bunch of ordinary people. Seriously. The Irish Parliament convened a citizens' assembly, whose 99 members were chosen at random. The selection process ensured that the group's composition represented the Irish population along dimensions such as age, gender and geography. Over several months in 2016 and 2017, the assembly heard expert opinions and held extensive discussions regarding the legalization of abortion. Its recommendation, supported by a significant majority of members, was to allow abortions in all circumstances, subject to limits on the length of pregnancy. These conclusions set the stage for a 2018 referendum in which 66 percent of Ireland's voters chose to repeal the Eighth Amendment, enabling abortion to be legalized. Such an outcome had been almost inconceivable a few years earlier.

The Irish citizens' assembly is just one example of a widespread phenomenon. In recent years hundreds of such groups have convened around the world, their members randomly selected from the concerned population and given time and information to aid their deliberations. Citizens' assemblies in France, Germany, the U.K., Washington State and elsewhere have charted pathways for reducing carbon emissions. An assembly in Canada sought methods of mitigating hate speech and fake news; another in Australia recommended ethical approaches to human genome editing; and yet another in Oregon identified policies for COVID pandemic recovery. Taken together, these assemblies have demonstrated an impressive capacity to uncover the will of the people and build consensus.

The effectiveness of citizens' assemblies isn't surprising. Have you ever noticed how politicians grow a spine the moment they decide not to run for reelection? Well, a citizens' assembly is a bit like a legislature whose members make a pact barring them from seeking another term in office. The randomly selected members are not beholden to party machinations or outside interests; they are free to speak their mind and vote their conscience.

What's more, unlike elected bodies, these assemblies are chosen to mirror the population, a property that political theorists refer to as descriptive representation. For example, a typical citizens' assembly has a roughly equal number of men and women (some also ensure nonbinary participation), whereas the average proportion of seats held by women in national parliaments worldwide was 26 percent in 2021—a marked increase from 12 percent in 1997 but still far from gender balance. Descriptive representation, in turn, lends legitimacy to the assembly: citizens seem to find decisions more acceptable when they are made by people like themselves.

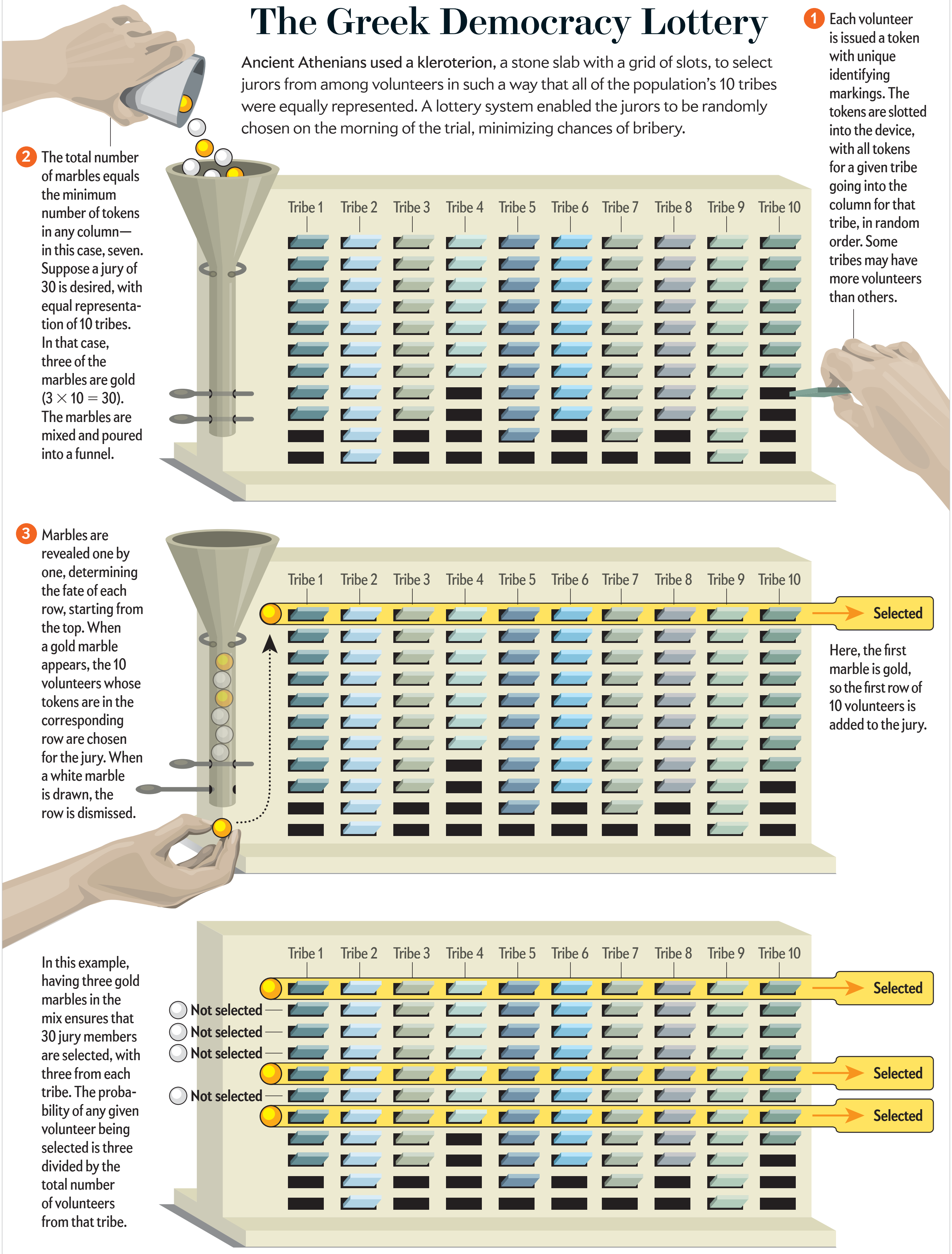
As attractive as descriptive representation is, there are practical obstacles to realizing it while adhering to the principle of random selection. Overcoming these hurdles has been a passion of mine for the past few years. Using tools from mathematics and computer science, my collaborators and I developed an algorithm for the selection of citizens' assemblies that many practitioners around the world are using. Its story provides a glimpse into the future of democracy—and it begins a long time ago.

THE GODDESS OF CHANCE

CITIZENS' ASSEMBLIES are the latest incarnation of an idea called sortition, the random selection of representatives, that dates back to classical Athens. In the fifth century B.C.E. the city-state,

The Greek Democracy Lottery

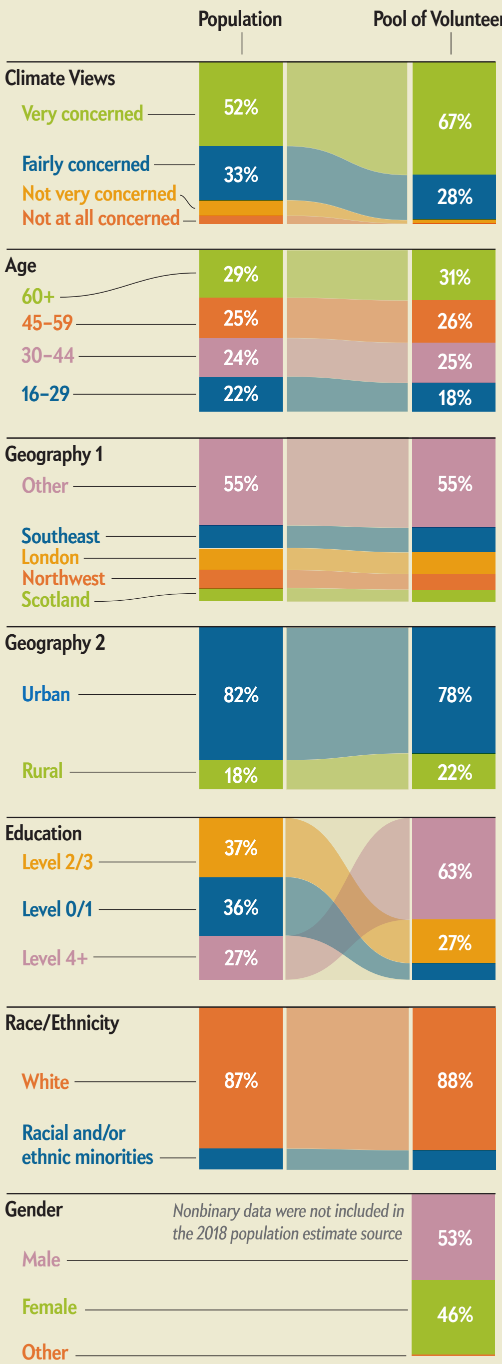
Ancient Athenians used a kleroterion, a stone slab with a grid of slots, to select jurors from among volunteers in such a way that all of the population's 10 tribes were equally represented. A lottery system enabled the jurors to be randomly chosen on the morning of the trial, minimizing chances of bribery.



Graphics by Jen Christiansen

A Skewed Pool of Volunteers

A citizens' assembly should resemble the populace, but its members are typically chosen from a pool of volunteers that does not. The 1,727 volunteers for Climate Assembly U.K. were particularly mismatched with the general population in their education levels and views on climate.



Source: Sortition Foundation (data)

whose patron deity was Athena, embraced sortition to such a degree that one might say it was de facto governed by Tyche, the goddess of chance. A large majority of its public officials were selected by lot from among citizens who volunteered to serve. These included most of the magistrates, who formed the executive branch, thousands of jurors, and the entire Council of 500, a deliberative body with a wide range of responsibilities.

The Athenians' respect for sortition is apparent in the ingenious design of their lottery machine, the kleroterion, which was used to select jurors. It's a stone slab with a grid of slots, arranged in 10 vertical columns, corresponding to the 10 Athenian tribes. Citizens who wished to serve as jurors presented their lottery ticket—bronze tokens with identifying information—to a magistrate, who inserted each tribe's tokens into the slots in the appropriate column. The magistrate also poured marbles of two contrasting colors—say, gold and white—through a funnel into a cylinder, where they lined up in random order.

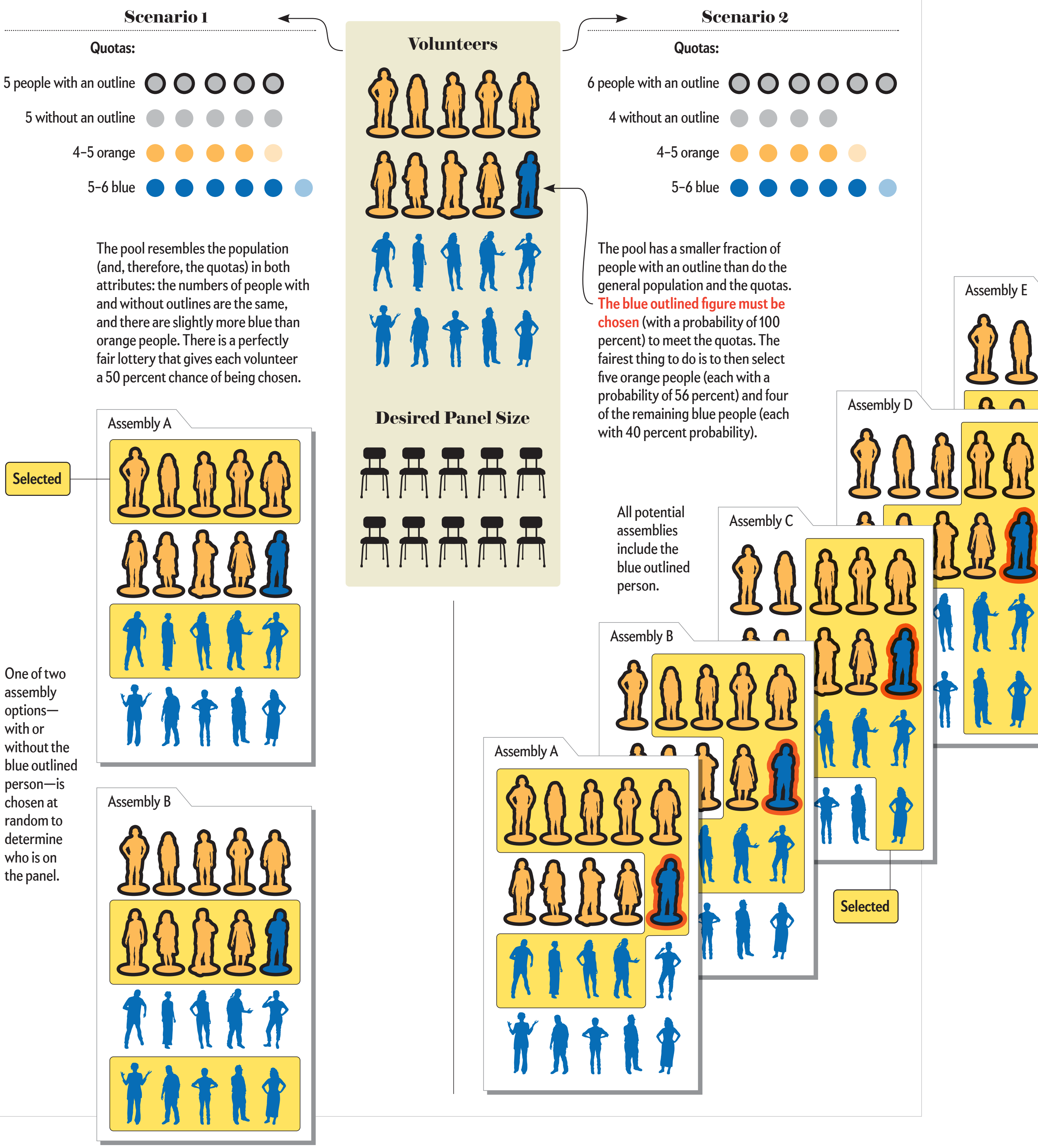
Then, the magistrate used a mechanism to reveal the marbles one by one. If the first marble was gold, the 10 citizens whose tokens appeared in the top row were added to the jury; if it was white, they were all dismissed. And so on, down the column of marbles and the rows of citizens: gold meant in; white meant out. To select a jury of 30 citizens, for example, the magistrate would include three gold marbles in the mix. Because each gold marble picks precisely one citizen from each tribe, any jury selected in this way would necessarily have an equal number of members from each tribe. This passed for descriptive representation in a society that practiced slavery and excluded women from the political process.

As clever as a kleroterion is, the present-day selection process for citizens' assemblies is more complicated because our concept of descriptive representation is much more nuanced. A citizens' assembly is expected to reflect many demographic attributes of the population, not just one. Take Climate Assembly U.K., which the House of Commons commissioned in 2019 to discuss how the nation should reach its target of zero greenhouse gas emissions by the year 2050. Organizers selected the 110 members randomly while seeking to represent the populace according to seven criteria: gender, age, geographic region, education, ethnicity, rural or urban residence, and climate views. Consider the rural-or-urban criterion: in the U.K., about 80 percent of the population lives in urban areas, so out of the 110 seats, 88 seats (or 80 percent) were reserved for urbanites, and 22 seats (or 20 percent) were allocated to country dwellers. Quotas were calculated similarly for each of the other criteria.

As if this isn't complicated enough, organizers of citizens' assemblies often face the challenge that they can select members only from among volunteers, and the pool of willing candidates may look nothing like the population. Typically the organizers issue invitations by mail or phone to a large number of people, but only a fraction of invitees opt in. For example, the organizers of Climate Assembly U.K. sent invitation letters to 30,000 households and mustered 1,727 volunteers. Of the latter, 63 percent had attained the highest level of education (in the British system), whereas a mere 27 percent of Britons fell into that category. It should also come as no surprise that the distribution of climate views among volunteers was skewed, with those concerned about the issue being overrepresented, compared with the general population: it is a rare climate skeptic who relishes

The Challenge of Fair Representation

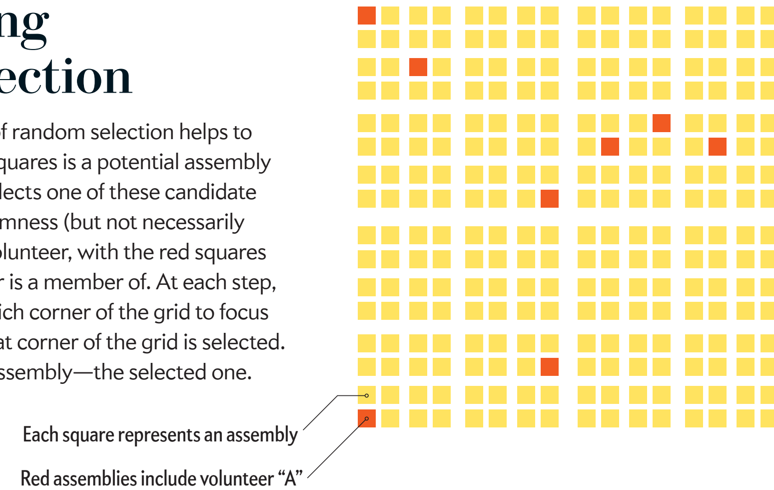
With a skewed volunteer pool, choosing an assembly that resembles the general population in multiple attributes is usually accomplished by filling quotas. If half the population is rural and half urban, so must the members be. In this example, 10 members reflecting the populace in two characteristics (*color* and *outline*) must be chosen from 20 volunteers.

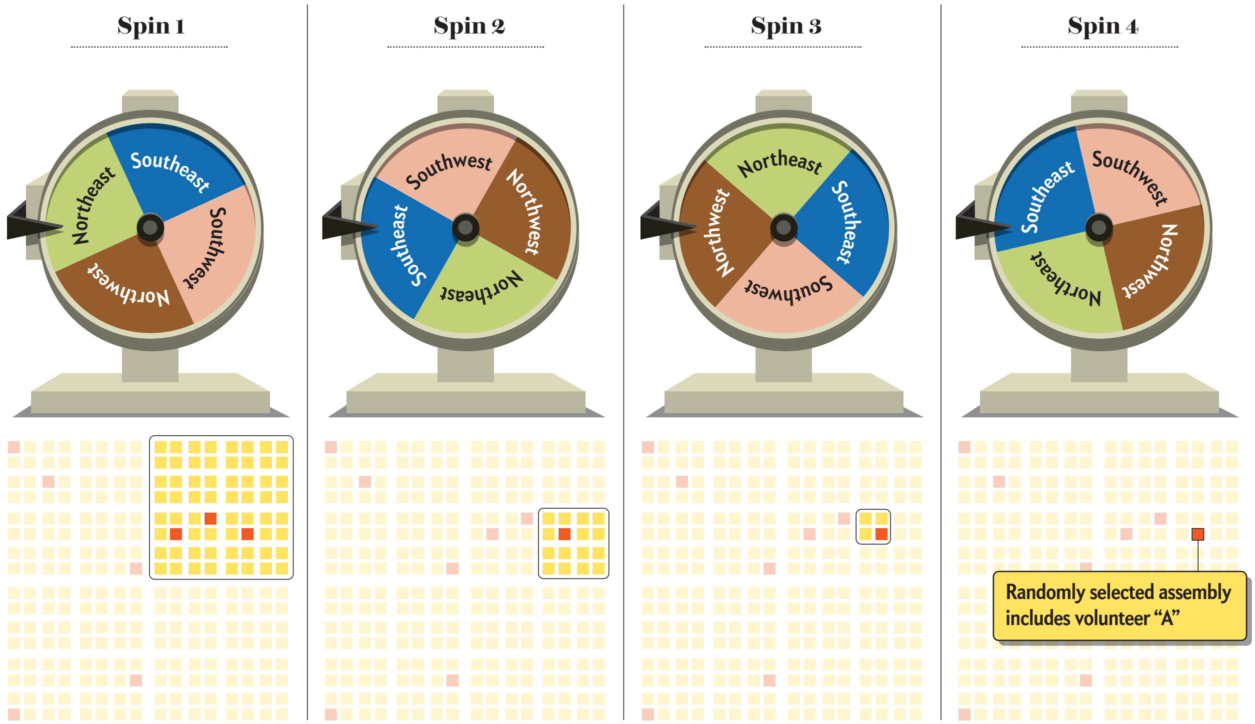


Wee People font, ProPublica and Alberto Cairo (*figure drawings*)

Visualizing Random Selection

As with the kleroterion, visualizing the process of random selection helps to increase trust. In this example, each of the 256 squares is a potential assembly meeting all the necessary criteria. The lottery selects one of these candidate assemblies as the actual one, with perfect randomness (but not necessarily fairness). This visualization takes the view of a volunteer, with the red squares being the potential assemblies that the volunteer is a member of. At each step, we spin the "wheel of fortune," and it tells us which corner of the grid to focus on. For example, the first spin is northeast, so that corner of the grid is selected. Three more spins, and we end up with a single assembly—the selected one.





the opportunity to spend long weekends charting a course to zero emissions.

To summarize, we need a modern-day kleroterion that can select a citizens' assembly that is representative in terms of multiple criteria—and can do so starting from an unrepresentative pool of volunteers. Thankfully, we've progressed from stone slabs to computers, so this problem boils down to the design of the right algorithm.

Until recently, the prevalent approach relied on what computer scientists call a "greedy algorithm." This is a bit of misnomer because such an algorithm is really guilty of sloth rather than greed: It takes the action that seems best right now, without making an effort to understand what would work well in the long term. To select an assembly, a greedy algorithm adds volunteers one by one in a way that makes the most immediate progress toward filling the quotas. For example, the algorithm might determine that, right now, the assembly is sorely missing individuals in the 30-to-44 age group, and among all volunteers in this age group, it would choose one at random to join the assembly. Next, it might identify a shortage of Londoners and select someone from that group.

The algorithm may make some bad choices and end up in a situation where it is unable to fill the quotas, but in that case, it can simply restart, and experience shows that it will eventually catch a lucky break. In fact, a particular greedy algorithm developed by a U.K.-based nonprofit, the Sortition Foundation, was used to select that country's climate assembly and many other consequential assemblies.

TO BE FAIR

IT WAS AN EXAMINATION of the greedy algorithm that instigated my own work on the selection of citizens' assemblies, done in collaboration with Bailey Flanigan and Anupam Gupta, both at Carnegie Mellon University, Paul Gölz of Harvard University and Brett Hennig of the Sortition Foundation. We realized that, in the greedy algorithm's short-sighted pursuit of filling quotas, it may sacrifice another important goal: giving all volunteers a fair chance of serving on the assembly. Political theorists view fairness as key to achieving democratic ideals such as equality of opportunity. To be sure, some imbalance is inevitable: Because the objective is descriptive representation of the entire population, volunteers who belong to groups that are underrepresented in the pool are more likely to be selected than those in overrepresented groups. In practice, however, the greedy algorithm excludes some volunteers from the process, even when it is unnecessary.

To see how the greedy algorithm is unfair, we can revisit the selection process of Climate Assembly U.K. by simulating the different assemblies put together by the algorithm, each of which could, in principle, have been the actual one. It turns out that the algorithm selects some of the 1,727 volunteers with a minuscule probability of less than 0.03 percent, whereas it is possible to guarantee that even the least fortunate volunteer is chosen with a probability of at least 2.6 percent—86 times higher—while meeting the same quotas.

We love to talk of "democratizing AI" or "democratizing finance," but democracy itself demands our attention.

To create a fairer algorithm, my collaborators and I adopt a holistic approach. Instead of considering volunteers one at a time, we consider the entire ensemble of potential assemblies, each of which meets all the demographic quotas. Each candidate assembly is given a lottery ticket that specifies its probability of being selected as the actual assembly. The probabilities are determined later, in such a way that they add up to 100 percent, and there's only one winning ticket.

Imagine that each volunteer is given a copy of the lottery ticket of every assembly of which they are a member. The volunteer is selected if any of their lottery tickets wins; in other words, the probability that a volunteer is selected is the sum of probabilities associated with all the potential assemblies that include them. Of all possible lotteries, our algorithm seeks to construct the fairest one, in the sense that the selection probability of the volunteer who is least likely to be chosen is as high as possible.

Now all we need to do is to go over all potential assemblies and … oh wait, the number of potential assemblies is beyond astronomical. A common way to illustrate "astronomical" is to compare the quantity in question with the number of atoms in the observable universe, estimated to be at most 10^{82}. But even that doesn't quite cut it: if you took every atom in the universe and replaced it with an entire universe, each with 10^{82} atoms, the total number of atoms you'd get is still much smaller than the number of ways to select the 110 members of Climate Assembly U.K. from the 1,727 volunteers (without quotas).

Fortunately, computational problems at this mind-boggling scale are routinely solved by machinery from the field of optimization. To apply these techniques, one must construct a mathematical model that includes an objective (in this case, maximizing fairness) and defines a set of possible solutions. The goal is to find the optimal (fairest) solution out of all possible solutions. In another example, when a navigation app such as Google Maps plans a trip from one location to another, it is solving an optimization problem wherein every feasible route is a possible solution and the objective is to find the shortest possible travel time. In a large city, the number of routes can be enormous, yet we take it for granted that our phones will comb through all these possible trips in seconds. The problem of finding the fairest lottery of the potential assemblies is a much harder problem, but it, too, can be conquered by the right combination of optimization tools.

Our algorithm was released as open source in 2020 and has since become a common method for selecting citizens' assemblies. It was initially adopted by our partners at the Sortition Foundation, who have used it to select, among others, Scotland's climate assembly, convened by the Scottish government; a citizens' jury on assisted dying in Jersey Island, which led to its parliament's decision to allow the practice in principle; and a public advisory group created by the U.K.'s National Health Service to discuss how the government should use data in its response to the COVID pandemic. Other organizations have employed our algorithm to select major citizens' assemblies in Germany, France and the U.S., including a panel in Michigan to chart a pathway for pandemic recovery. Last year, thanks to an effort led by Gölz and Gili Rusak, a doctoral student at Harvard, our algorithm became freely accessible through the website Panelot.org (panel selection by lot), making it even easier for practitioners to apply it.

THE DEMOCRACY CODE

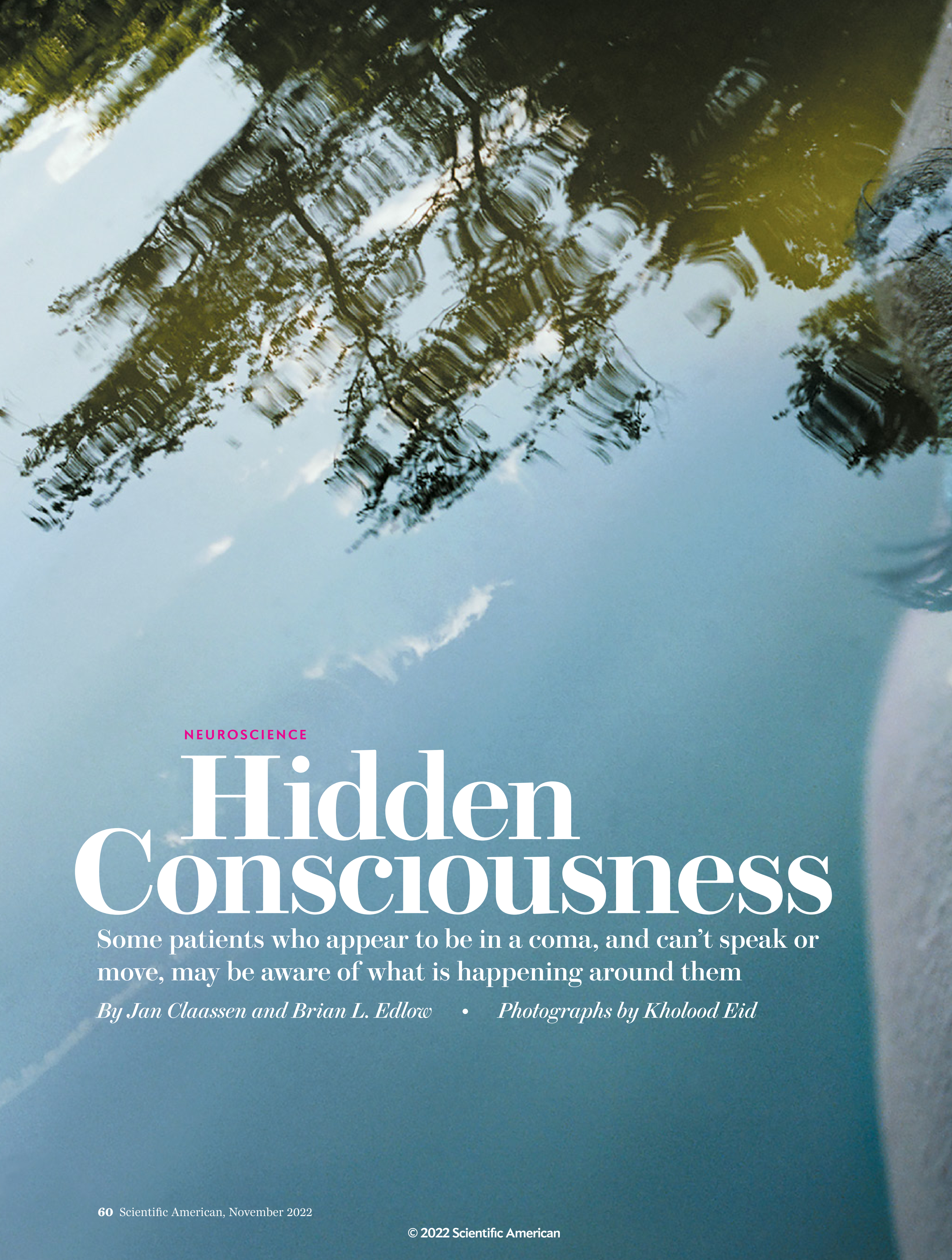
AN AMERICAN TIME TRAVELER visiting the present from the late 18th century would find an almost unrecognizable world, but one thing, at least, would look eerily familiar: the way our system of democracy works. Although the endurance of the political system is a tribute to the framers of the constitution, it's abundantly clear that not all is well. In America and in some other democracies around the world, faith in governments has hit rock bottom, and even the most popular legislation often fails to be enacted. There's an urgent need to rethink the practice of democracy using modern tools.

I believe that mathematicians and computer scientists have a significant role to play in this endeavor. We love to talk of "democratizing AI" or "democratizing finance," but democracy itself demands our attention. An algorithmic approach is crucial to the construction of new frameworks to engage citizens and give them a voice. But this apparatus of democracy comes with uniquely challenging instructions: "random assembly required." SA

FROM OUR ARCHIVES

Geometry v. Gerrymandering. Moon Duchin; November 2018.

scientificamerican.com/magazine/sa



NEUROSCIENCE

Hidden Consciousness

Some patients who appear to be in a coma, and can't speak or move, may be aware of what is happening around them

By Jan Claassen and Brian L. Edlow • Photographs by Kholood Eid

Jan Claassen is an associate professor of neurology at Columbia University and a critical care neurologist at New York–Presbyterian Hospital at Columbia University, where he is chief of critical care and hospitalist neurology and head of the disorders of consciousness laboratory.

Brian L. Edlow is an associate professor of neurology at Harvard Medical School and a critical care neurologist at Massachusetts General Hospital, where he directs the Laboratory for Neuroimaging of Coma and Consciousness and is associate director of the Center for Neurotechnology and Neurorecovery.

A MEDICAL TEAM SURROUNDED MARIA MAZURKEVICH'S HOSPITAL BED, ALL eyes on her as she did … nothing. Mazurkevich was 30 years old and had been admitted to New York–Presbyterian Hospital at Columbia University on a blisteringly hot July day in New York City. A few days earlier, at home, she had suddenly fallen unconscious. She had suffered a ruptured blood vessel in her brain, and the bleeding area was putting tremendous pressure on critical brain regions. The team of nurses and physicians at the hospital's neurological intensive care unit was looking for any sign that Mazurkevich could hear them. She was on a mechanical ventilator to help her breathe, and her vital signs were stable. But she showed no signs of consciousness.

Mazurkevich's parents, also at her bed, asked, "Can we talk to our daughter? Does she hear us?" She didn't appear to be aware of anything. One of us (Claassen) was on her medical team, and when he asked Mazurkevich to open her eyes, hold up two fingers or wiggle her toes, she remained motionless. Her eyes did not follow visual cues. Yet her loved ones still thought she was "in there."

She was. The medical team gave her an EEG—placing sensors on her head to monitor her brain's electrical activity—while they asked her to "keep opening and closing your right hand." Then they asked her to "stop opening and closing your right hand." Even though her hands themselves didn't move, her brain's activity patterns differed between the two commands. These brain reactions clearly indicated that she was aware of the requests and that those requests were different. And after about a week, her body began to follow her brain. Slowly, with minuscule responses, Mazurkevich started to wake up. Within a year she recovered fully without major limitations to her physical or cognitive abilities. She is now working as a pharmacist.

Mazurkevich had "covert consciousness," a state in which the brain reacts to the outside world with some comprehension, although the body does not respond. As many as 15 to 20 percent of patients who appear to be in a coma or other unresponsive state show these inner signs of awareness when evaluated with advanced brain-imaging methods or sophisticated monitoring of electrical activity. Many of these techniques have only recently been refined. These methods are altering our understanding of coma and other disorders of consciousness. Moreover, people whose covert consciousness is detected early have a greater chance of a full conscious and functional recovery, indicated by our studies at Columbia University. These discoveries, which would have startled most neurologists and neuroscientists a few decades ago, highlight the importance of recognizing this hidden conscious state and developing ways to communicate with people who are in it.

THE STANDARD DEFINITION OF A COMATOSE PATIENT IS SOMEONE WHO IS unconscious, is unable to be awakened, and has no signs of awareness or the ability to interact with the environment. Patients in a coma caused by severe brain injury may look indistinguishable from someone in a deep sleep, except that most comatose patients cannot breathe on their own and need support from a ventilator, with a tube inserted into their airway.

Some people think comas are easy to recover from or—conversely—a living death. Both are mistakes. Popular depictions in movies and elsewhere may be partly responsible for this. Uma Thurman as the Bride in *Kill Bill: Volume 1* awakens abruptly from a prolonged comatose state, appears well nourished despite not having any feeding tubes and regains full physical strength within hours. The reality is far more challenging, with frequent medical complications, physical deterioration and a long road of

AFTER A BRAIN INJURY, Maria Mazurkevich seemed to be in a coma. But brain tests showed she was aware, and she recovered in a year.

small steps forward with many steps backward. Patients who survive coma after severe brain injury typically require feeding tubes for nutrition, tracheostomies that allow them to breathe through a tube in the neck and weeks to months of rehabilitation. Recovery is variable and unpredictable, even in those who, like Mazurkevich, ultimately return to independence. Overly pessimistic views of coma patients are also inaccurate because people may assume that all such patients are destined to die without emerging from their coma or live with severe disability. Recovery of consciousness, communication and functional independence is quite possible in some patients, even after a prolonged time.

Views about coma and consciousness have changed in the medical profession over time. In the 1960s neurologists and neurosurgeons noted that some comatose patients opened their eyes but showed no interaction with the environment. Many of these people remained in this state until death, leading some clinicians to believe that consciousness, once lost in this way, was impossible to recover.

Immobile patients with covert consciousness can deliberately alter their brain patterns when told to move parts of their bodies.

Yet in the 1990s reports of patients in a "permanent" vegetative state who returned to consciousness began to surface in the medical literature. In a vegetative state, unlike coma, people's eyes may open and shut, but they still do not react in any deliberate manner. The reports of recovery from this condition pushed the fields of neurocritical care and rehabilitation medicine to develop more fine-tuned classifications such as the minimally conscious state. It is characterized by nonverbal responses, as when patients track objects with their eyes or intermittently follow commands. A patient's prognosis, physicians learned, was related to these states. For instance, someone who moved from a vegetative to a minimally conscious state had a greater chance of further recovery.

Detecting and predicting recovery of consciousness early on, in the intensive care unit, is often a matter of life or death. Families typically make decisions about continuing or stopping life-sustaining therapy within 10 to 14 days of the injury—the time when surgical procedures become necessary to support longer-term breathing and feeding. And a diagnosis of covert consciousness could affect clinical decisions about goals of care, pain management, bedside behavior of clinicians and family members, and management of depression and anxiety.

SO WHAT DOES COVERT CONSCIOUSNESS LOOK LIKE TO CLINICIANS AND TO the patient's family? One can get some idea through the lens of locked-in syndrome, in which people may have normal or near-normal cognition but are unable to control most motor movements. Locked-in patients illustrate the limitations of judging awareness, thinking abilities, and emotions purely based on motor function. The term "locked in" was coined in 1966 by neurologists Fred Plum and Jerome Posner in their monograph *The Diagnosis of Stupor and Coma*. They refer to the description of M. Noirtier De Villefort as "a corpse with living eyes" in Alexandre Dumas's classic *The Count of Monte Cristo* (1844–1846). In clinical practice, locked-in patients do not move their extremities, but many can reliably move their eyes up and down in response to verbal commands. Some can blink or show other subtle facial movements.

The experience of living in a locked-in state was poignantly illustrated by Jean-Dominique Bauby, an editor at *Elle* magazine who, in 1995, suffered a stroke that blocked signals traveling from the motor cortex in his brain to his spinal cord and limbs. Without the ability to speak or move his extremities, he began to communicate with his speech therapist using eye movements and wrote a memoir, *The Diving Bell and the Butterfly* (1997). This book captured the fear, frustration and hope that individuals with locked-in syndrome may experience. Remarkably, some people in a locked-in state report a meaningful quality of life.

With covert consciousness, the lack of outward movement is complete, even more so than with locked-in patients. But this does not mean the absence of inner life. In 2006 neuroscientist Adrian M. Owen, now at Western University in Ontario, and his colleagues examined a young woman who had experienced a severe traumatic brain injury and was believed to be in a vegetative state. The health-care team assessed her with a type of imaging scan called functional MRI, which traces blood flow through the brain to reveal active areas. During this scan the clinicians asked her to imagine playing tennis and to imagine walking through the rooms of her house. To the surprise of Owen and his colleagues, the woman showed activation within her brain comparable to that seen in healthy volunteers. What's more, the brain-activation patterns for the tennis task were distinct from the patterns in the walking task, indicating that she could deliberately change her brain activity.

Covert consciousness was subsequently identified in patients around the world, with varying types of brain injuries. In 2017 it was detected in seemingly unaware patients who had just been admitted to the intensive care unit at Massachusetts General Hospital with severe brain injuries, indicating that the covert phenomenon can occur in people who had very recently been hurt, not only after patients have been "out" for weeks. To diagnose the covert state, clinicians use different behavioral tasks, such as asking the patient to open and close their hands or imagine swimming while recording their brain reactions with an EEG or functional MRI. These responses have been reproduced by multiple research groups worldwide despite differences in methodology. Patients with covert consciousness can deliberately alter their brain patterns when told to move parts of their bodies or to envision an activity. But outwardly, in terms of body movements, they show no signs of following any prompt.

This state of being in which cognitive function exceeds motor expression is still poorly understood, and both the EEG and functional MRI techniques have limitations. The methods may not detect intentional brain activity in some patients who later regain consciousness. Both techniques may also be confounded by sedative medications, which are required for safety or comfort in most critically ill patients. Furthermore, functional MRI requires a specialized imaging room, and moving unstable patients from the intensive care unit to the MRI scanner may put them at risk. Yet another problem is that the MRI provides only a snapshot of a patient's level of consciousness during a short period because it cannot easily be repeated. An EEG can be done frequently at the patient's bedside—capturing snapshots at different times—but the method has its own shortcomings. Its readings can be altered by electrical noise created by other machines in intensive care rooms, which can cause the test to reflect artifacts instead of reality.

Both methods need improvements, but the evidence for their usefulness is strong enough for them to be endorsed for the diagnosis of covert consciousness in clinical guidelines in the U.S. (2018) and Europe (2020). The early detection of covert consciousness, soon after a patient's injury, predicts behavioral recovery of consciousness, long-term functional recovery and the speed of that recovery, as shown by the research that our group published in 2019 (and confirmed more recently, in 2022). Building on the momentum of these studies, scientists came together in 2019 to launch the Curing Coma Campaign, an international collaboration led by the Neurocritical Care Society to direct medical resources and public attention to the condition, with the goal of developing new therapies that promote recovery of consciousness.

Neurologists are trying to develop a test that can identify which patients are likely to be in a state of covert consciousness and thus should undergo advanced EEG and functional MRI assessments. Laboratories around the world are working to develop such screening methods, but progress has been slow because the structural and functional mechanisms that underlie covert consciousness are uncertain, so clinicians do not know exactly what to look for. Recent studies suggest that brain injuries disconnecting the thalamus—a region that relays movement signals and sensory information between the body and brain—from the cerebral cortex, which is responsible for higher-level cognitive functioning, may be responsible for the condition. Yet it is likely that not a single type of lesion but rather various combinations of lesions in several locations could cause motor dysfunction while allowing covert consciousness. Further complicating clinical efforts to detect covert consciousness is that patients with severe brain injuries often have fluctuating levels of consciousness. Such swings mean that a single assessment could miss important signs; perhaps patients need to be tested multiple times.

BUILDING ON RECENT DISCOVERIES ABOUT THE PRESENCE OF COVERT consciousness, investigators are trying to reconnect and communicate with these patients using brain-computer interfaces. These devices typically record the brain's electrical activity while asking the patient to move the cursor of a mouse on a computer screen. The computer "learns" to identify the physiological signals that correlate with the patient's attempts to move the cursor, left, right, up or down. Once training is completed, those brain patterns allow the patient to take control over the cursor. Patients can use it to select letters and spell out words.

Brain-computer interfaces would be ideal to provide covertly conscious patients a communication channel with the outer world. But tremendous challenges must be overcome, particularly for acutely brain-injured patients. The capacity for sustained attention in these patients may be compromised, and prolonged training is often not feasible. Moreover, the hectic, noisy intensive care environment is not ideal for these purposes. For example, even though Mazurkevich had covert consciousness that was associated with a very good recovery, she was unable to activate a brain-computer interface to communicate with the health-care team or her family.

Communication might be possible using functional MRI, too. A few years ago Martin Monti, a cognitive psychologist at the University of California, Los Angeles, used the method to investigate the presence of covert consciousness in a group of behaviorally unresponsive patients. He wanted to see if he could train them to reliably answer "yes" or "no" to questions by using different functional MRI activation patterns. This required enormous technological coordination as the imaging data needed to be analyzed in real time. As Owen did in 2006, Monti asked patients to imagine playing tennis or imagine walking through their apartment. The difference was that he wasn't simply looking for brain activation; he wanted to see if they understood questions well enough to answer them. He told them to think about tennis if the answer to a given question was "yes" and think about walking through their home if the answer was "no." Monti identified one patient in the group who reliably communicated with him using this strategy, creating one pattern of brain activity for yes answers and another pattern for no answers. Although there are questions about whether this approach can be scaled up for wider use, his study suggested that communication with patients in a state of covert consciousness is possible.

To further improve communication, reliable tools to identify patients with covert consciousness need to be at the bedside. A number of groups are investigating advanced EEG technology because this can more easily be integrated into the clinical routine of an intensive care unit. And with brain-computer interfaces, the accuracy of the algorithm that decodes the patient's attempts to control the computer might be enhanced by using additional biological signals, such as heart rate, along with brain activity.

Beyond the urgent matter of caring for critically ill patients, diagnosis and exploration of covert consciousness have the potential to teach us about the human mind. In covert consciousness, the very foundation of our experience as humans, our consciousness, is dissociated from our behavior. What is the inner mental life of the covertly conscious patient? Detecting covert consciousness fundamentally affects our conceptualization of an individual's personhood and autonomy. Brain-computer interfaces have not yet allowed in-depth conversations, and to date patients with covert consciousness who recovered the ability to communicate and were interviewed later did not remember the experience of being covertly conscious. Mazurkevich, for instance, does not recall any aspect of her time in the intensive care unit when she appeared to be comatose. So the experience is still largely a mystery.

There is no mystery, however, about the ethical imperative that physicians now have to search for consciousness in patients who appear unresponsive, using all available technologies and resources. Increasing access to these technologies and resources is a fundamental goal, and challenge, for the medical community, spearheaded by the Curing Coma Campaign. With those tools, we can look forward to a future in which all covertly conscious people are given a way to speak for themselves. SA

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Uncanny Sight in the Blind. Beatrice de Gelder; May 2010.
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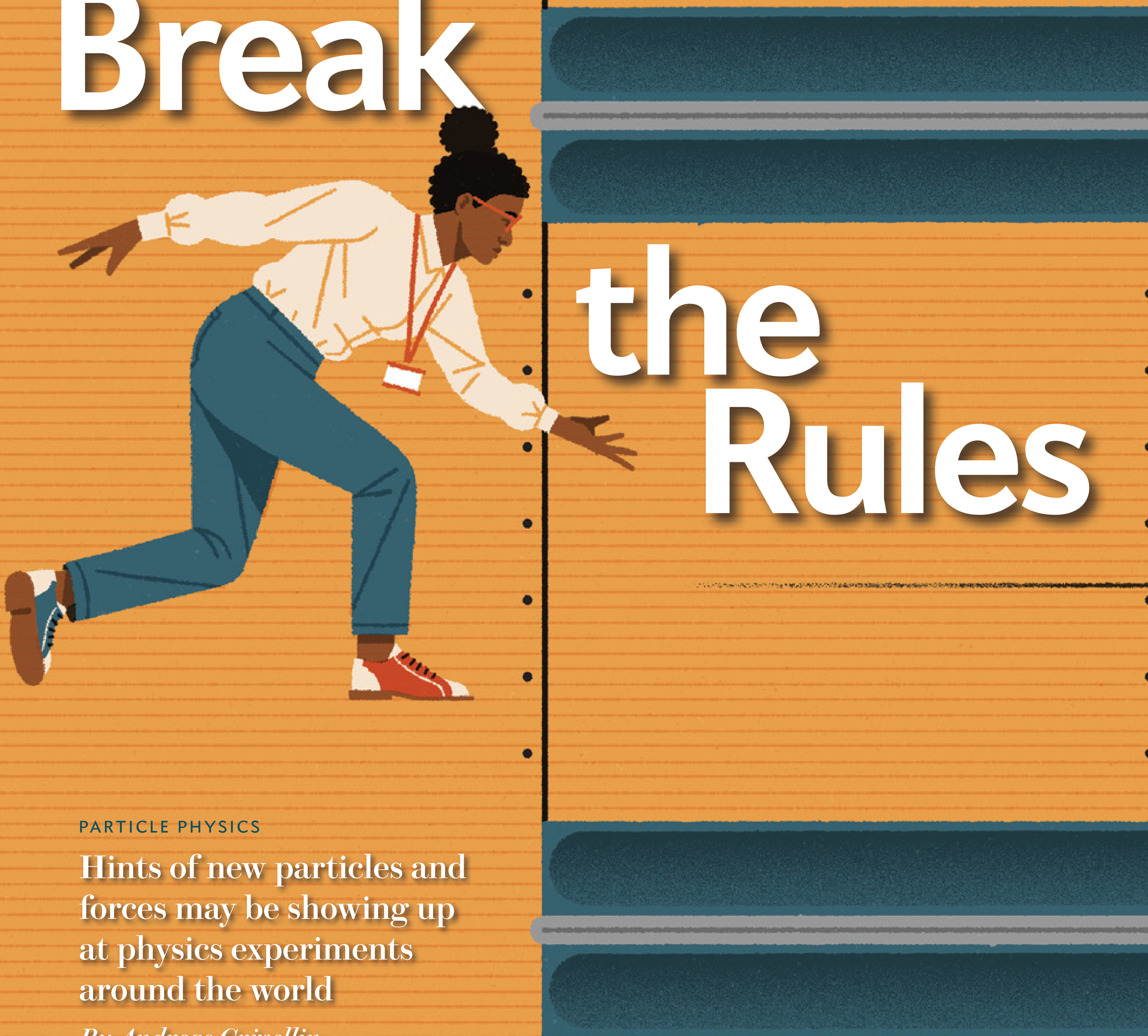
When Particles Break the Rules

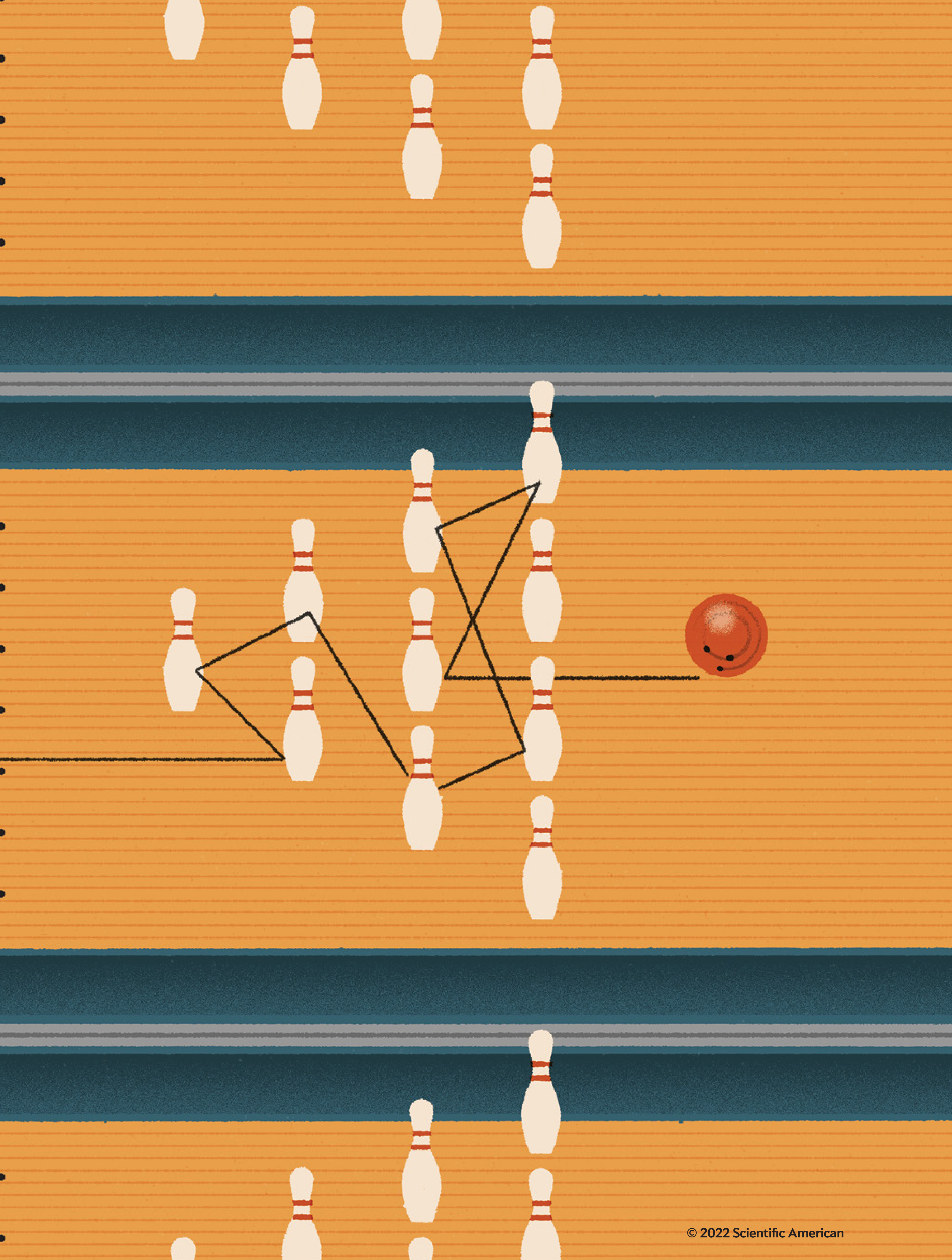


PARTICLE PHYSICS

Hints of new particles and forces may be showing up at physics experiments around the world

By Andreas Crivellin

Illustration by Matt Harrison Clough



Andreas Crivellin is a theoretical physicist at the University of Zurich and the Paul Scherrer Institute in Switzerland.

BREAKING THE RULES IS EXCITING, ESPECIALLY IF THEY HAVE held for a long time. This is true not just in life but also in particle physics. Here the rule I'm thinking of is called "lepton flavor universality," and it is one of the predictions of our Standard Model of particle physics, which describes all the known fundamental particles and their interactions (except for gravity). For several decades after the invention of the Standard Model, particles seemed to obey this rule.

Things started to change in 2004, when the E821 experiment at Brookhaven National Laboratory on Long Island announced its measurement of a property of the muon—a heavy version of the electron—known as its g-factor. The measurement wasn't what the Standard Model predicted. Muons and electrons are both part of a class of particles called leptons (along with a third particle, the tau, as well as the three generations of neutrinos). The rule of lepton flavor universality says that because electrons and muons are charged leptons, they should all interact with other particles in the same way (barring small differences related to the Higgs particle). If they don't, then they violate lepton flavor universality—and the unexpected g-factor measurement suggested that's just what was happening.

If particles really were breaking this rule, that would be exciting in its own right and also because physicists believe that the Standard Model can't be the ultimate theory of nature. The theory doesn't explain why neutrinos have mass, nor what makes up the invisible dark matter that seems to dominate the cosmos, nor why matter won out over antimatter in the early universe. Therefore, the Standard Model must be merely an approximate description that we will need to supplement by adding new particles and interactions. Physicists have proposed a huge number of such extensions, but at most one of these theories can be correct, and so far none of them has received any direct confirmation. A measured violation of the Standard Model would be a flashlight pointing the way toward this higher theory we seek.

A TRIP TO ELBA

THE E821 EXPERIMENT and the discovery of mysterious muon behavior happened before my time in particle physics. I got involved in the business of lepton flavor universality violation about 10 years ago, as a postdoc in Bern, Switzerland, when I was invited to a meeting about the proposed SuperB collider to be built in Tor Vergata near Rome. The meeting was being held on the picturesque Italian island of Elba on the Tyrrhenian Sea. Though picturesque, the island is not easy to reach. The invitation was on short notice; I quickly booked a train to Pisa but missed the conference bus. Fortunately, two of the organizers offered to take me along in their car to Elba. This ride proved fortuitous.

As we drove through beautiful landscapes, we chatted about physics. One of the scientists, an experimentalist named Eugenio Paoloni, asked me what I thought about the new measurements of B meson decays by the BaBar experiment in California, which pointed toward a violation of lepton flavor universality. B mesons are particles containing a beauty quark, and they are some of physicists' favorite particles to study because they decay in a variety of ways that have the potential to reveal new secrets of physics. I hadn't heard about the BaBar result, probably because at the time it hadn't attracted much attention. But I quickly thought of a possible explanation for the measurement—a new Higgs boson, in addition to the conventional one we know of, could cause the phenomena seen at BaBar. My interest in the topic of lepton flavor universality violations was born.

The rest of the workshop was uneventful. After the first day, the focus was on the development of the collider, and as a theorist I didn't understand a word the experimentalists were saying. So I enjoyed Elba and worked on a paper about my Higgs boson idea, which I finished shortly after my return to Bern. The article got published, but unfortunately the SuperB project was canceled, and the reactions of my colleagues to the paper were not enthusiastic, to say the least: "A year from now there will be nothing left to explain by new physics" was a typical response, meaning that the measurement was probably a statistical fluke and the anomaly would disappear with more data.

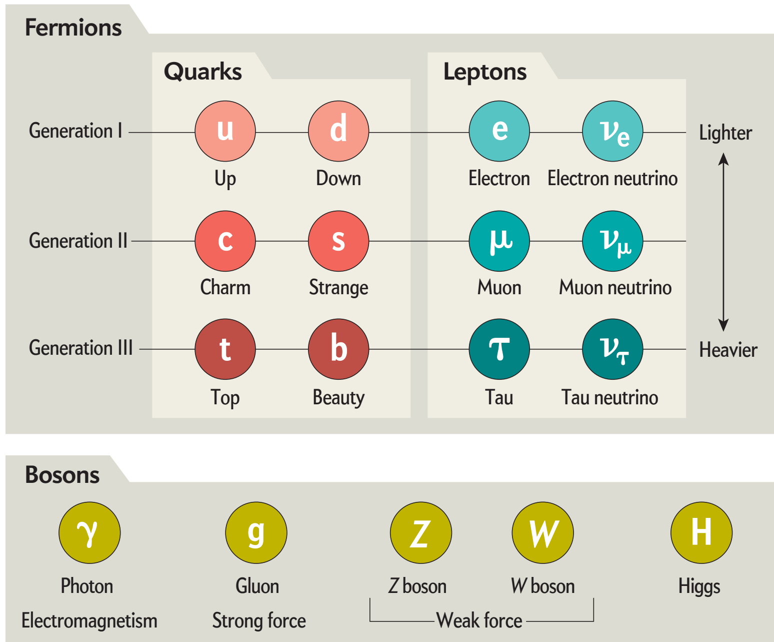
For some time after the BaBar findings, there were no new results related to this question, and things grew quiet. But then, in 2013, the LHCb experiment at the Large Hadron Collider (LHC) at CERN near Geneva observed a deviation from the Standard Model prediction in a complicated quantity called P_5' ("P-five-prime") related to how B mesons decay. On the surface, this quantity is not related to lepton flavor universality, and I didn't find the measurement very exciting at first. My feelings changed a year later, however, when LHCb analyzed a ratio called R(K), which *is* a measure of lepton flavor universality violation. The experiment found a deviation from the standard expectation, and it agreed with the P_5' findings, indicating that some new phenomenon might be occurring in muons.

A little while later the story hit a turning point, again at a conference. It was once more in Italy, this time in the charming village of La Thuile in the Alps, close to Mont Blanc. During the afternoon session after the skiing break, a partial eclipse of the sun took place. Just as amazing, scientists from LHCb announced a result that confirmed the previous P_5' measurement with more statistics—and my theory friends Joaquim Matias (called Quim) and David Straub agreed on the interpretation of these data. They had never agreed before. After thanking the speakers, I said to the audience, "Today we witnessed a rare event, a partial eclipse of the sun; however, that Quim and David agree for the first time is even more remarkable."

From then on, the evidence for lepton flavor universality violation has continued to grow. Lepton universality is an old rule, and it has been many years since we last saw a part of the Standard Model be disproved. If the rule has truly been broken, there must be new interactions and new particles in the universe that we don't know about—potentially particles that could help solve some of the biggest mysteries of our time.

The Standard Model

The known particles in the universe include fermions and bosons. Fermions are the building blocks of matter (including electrons and the quarks that form protons and neutrons). Each type of fermion comes in three varieties, called generations, that differ only in mass. Bosons carry the fundamental forces of nature. These forces shouldn't treat fermions of subsequent generations differently.



BACK TO BASICS

TO FULLY UNDERSTAND lepton flavor universality and what violating it means, we first have to review the known constituents of matter at the subatomic scale and the interactions among them—that is, the Standard Model. The building blocks of matter are called fermions, after the great physicist Enrico Fermi. These matter particles come in three versions, called generations, that are the same in every way except for their mass. For instance, the electron has heavier versions called muons and taus, the up quark has heavier relatives named charm and top quarks, and the down quark is followed by strange and beauty quarks. Only the light flavors are stable—they constitute the ordinary matter our world is made of. (Two up quarks and a down quark make a proton, and one up quark and two down quarks make a neutron.)

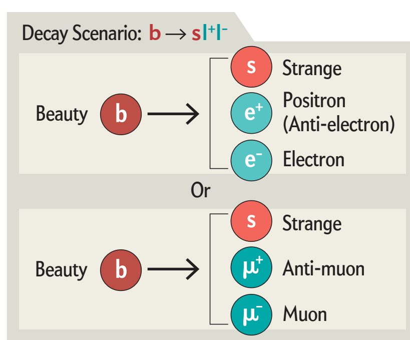
In addition to these particles, there are three forces through which the fermions can interact: the weak force, the strong force and the electromagnetic force (gravity is disregarded in the Standard Model because it is extremely weak at the subatomic scale). The corresponding force particles are called the *W* and *Z* bosons (for the weak force), gluons (for the strong force) and photons (for the electromagnetic force). Crucially, none of these interactions distinguishes among the three generations of fermions. The only thing that differentiates between the flavors is the famous Higgs boson, which is responsible for the fermions' differing masses.

Or so we thought. If leptons are not universal—if there are forces that do discriminate among the generations—then something interesting is afoot. So far we have four different indications that lepton flavor universality might not hold true.

$b \rightarrow sl^+l^-$

THE FIRST COMES FROM MEASUREMENTS of a particle decay process labeled $b \rightarrow sl^+l^-$, where the b represents a beauty quark, s is a strange quark and l is a charged lepton (either an electron or a muon). During this process the beauty quark turns into a strange quark and produces a pair of leptons—specifically, a lepton and its antimatter partner. We would expect these classes of decays to give rise to muons approximately as often as electrons. Yet experiments that have measured these processes, such as LHCb, observe more electrons than muons, suggesting an imbalance. The combined experimental data now indicate that there is at most a 0.0001 percent chance this difference is only a statistical fluke.

Theorists have proposed various new

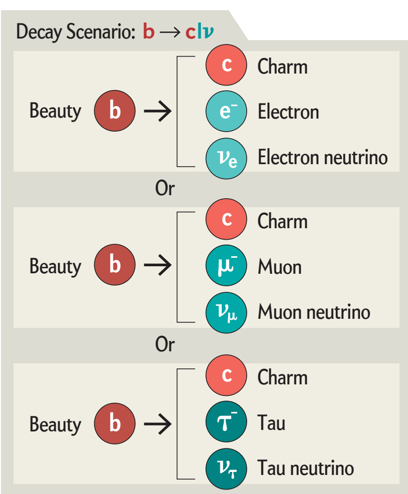


Graphics by Jen Christiansen

particles and forces that can describe the data better than the Standard Model. How, one might ask, can one account for a lack of muons by adding new particles? Explaining a deficit through an addition might seem contradictory, but this would be the case only in classical physics. In the quantum realm, it makes perfect sense. Because all particles also have wave properties, quantum mechanics predicts so-called virtual particles that appear and disappear all the time in empty space. These particles can interfere with the decay processes of regular particles, causing the decay rates to change from what the Standard Model predicts. One possibility here, for instance, is that the beauty quark, on its way to turning into its usual decay products, briefly interacts with a virtual heavy version, a new Z boson (called Z') that, contrary to the standard Z particle, does distinguish between muons and electrons.

b → clυ

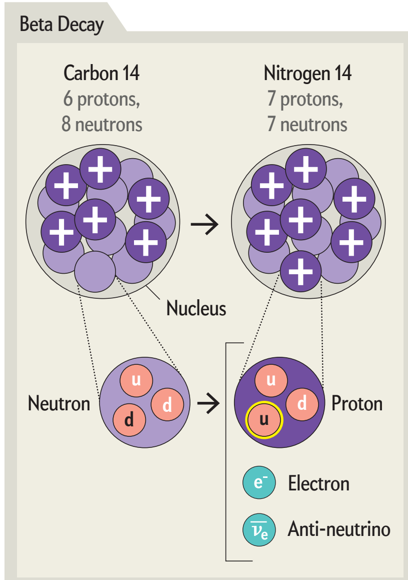
THE SECOND PIECE OF EVIDENCE for lepton universality violations comes from observing a beauty quark decaying into a charm quark (c), a lepton (l) and a neutrino (υ). Here tau leptons are expected less frequently than muons or electrons because they are heavier. Yet experiments such as BaBar, LHCb and an experiment in Japan called Belle have found that decays to tau particles happen more often than expected. Furthermore, the decays to muons and electrons show a relative asymmetry not expected in the Standard Model. Again, virtual particles may be interfering with the usual decay pathways. For instance, the beauty quark may interact with a virtual charged Higgs particle



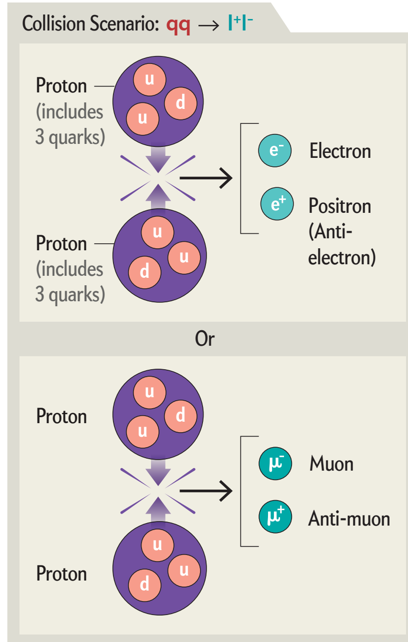
such as the one I proposed in 2012 (although this model now has some problems) or with another proposed novel particle referred to as a leptoquark.

CABIBBO ANGLE ANOMALY AND $qq \to e^+e^-$

ANOTHER INTRIGUING SIGNAL comes from certain radioactive decays called nuclear beta decays. Experiments have observed that these decays happen less frequently than expected. Beta decays occur within atomic nuclei, when down quarks transform into up quarks, or vice versa, allowing a neutron to become a proton, or the reverse, by emitting an electron and an antineutrino, or a positron (the antimatter counterpart of the electron) and a neutrino. When physicists combined their measurements with improved theoretical calculations, they realized that the particles within nuclei live longer than expected. This finding, called the Cabibbo Angle Anomaly, can be interpreted as another sign that electrons and muons might behave differently.



Furthermore, the CMS experiment at the LHC observed collisions of two protons that resulted in high-energy electrons (**$qq \to e^+e^-$**) and found that more electrons were produced in comparison to muons than expected, again pointing toward the violation of lepton flavor universality. This measurement and the Cabibbo Angle Anomaly could be related because the same interaction might suppress radioactive decays but also enhance the production of high-energy electrons.



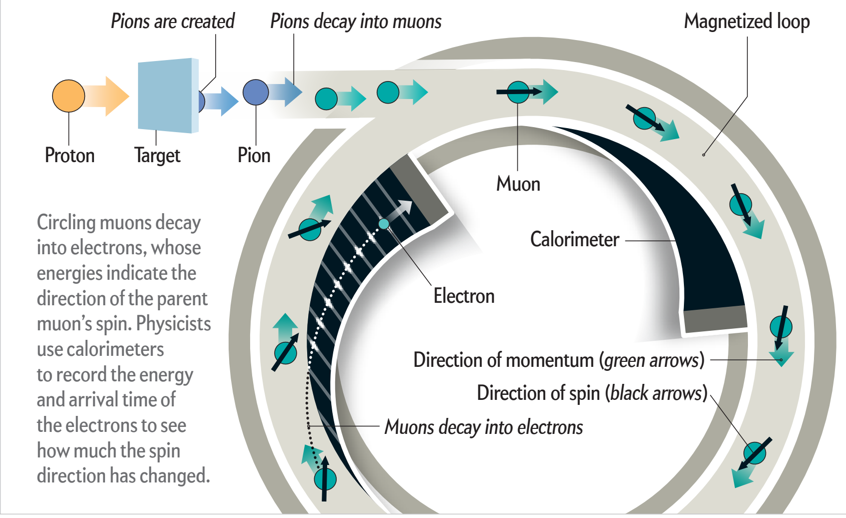
THE MAGNETIC MOMENT OF THE MUON

THIS TERM DESCRIBES how strongly a muon interacts with a magnetic field. Physicists quantify it with a g-factor, which we can predict very precisely with the Standard Model. Yet the Brookhaven experiment and the latest results coming from the G-2 experiment at Fermilab deviate from this prediction. The G-2 project sends muons around a magnetized ring and measures how their spins change as they travel. If muons were alone in the experiment, their spins would not change—but virtual particles arising around them can tug on the muons, introducing a wobble to their spins. Of course, the known particles can appear as virtual particles to cause this effect, but the Standard Model calculation accounts for that. If there are more particles in nature than the ones we are aware of, however, the experiment will see an extra wobble—and it does.

The combined results from the G-2 experiment and the previous trial at Brookhaven add up to a probability of less than 0.01 percent that this anomaly is a statistical fluke. Yet the Standard Model prediction that enables this calculation is itself questionable. It is based on other experimental results (for example, from BaBar and the KLOE project in Italy) that do not agree with simulations of quantum field theory that were recently performed on supercomputers.

The G-2 Experiment

Some of the most intriguing signs that particles are breaking the rules of physics are measurements of muons, the heavier cousins of electrons. The G-2 experiment at Fermi National Accelerator Laboratory in Batavia, Ill., recently measured how muons' spins change as they circle within a magnetic field, and it came up with a different value than predicted. One interpretation is that novel, undiscovered particles are interfering with the muons' spin, adding an extra wobble.



A NEW PARTICLE ZOO

IF WE MUST EXTEND the Standard Model to account for these anomalies, how should we do it? In other words, how can we modify the equations describing nature so that theory and experiment agree?

Particles in one promising class that are capable of explaining these measurements are called leptoquarks. They connect a single quark directly to a single lepton: for instance, a lepton could transform into a quark by emitting a leptoquark—unlike any interaction in the Standard Model. Such a particle would be something radically new. It has been proposed in the past in the context of grand unified theories, which were devised to unite the different forces in the Standard Model at high energies. These high energies, however, would correspond to particles that are very heavy. Physicists would need to alter existing grand unified models to create a leptoquark light enough to affect the measurements we have discussed.

Another option involves other new particles, such as heavy fermions, heavy "scalar" particles (including new Higgs bosons), or novel gauge bosons (similar to the *W* and *Z* bosons). One intriguing way to predict such particles is by using theories that contain, in addition to our four dimensions (three of space and one of time), at least one extra dimension, compactly folded up and hidden within the ones we know.

Although these hints we have for new phenomena are very intriguing—at least in my view—it's critical that we corroborate these hints with additional, more precise data and more accurate theoretical calculations. A number of experiments and theoretical collaborations worldwide are working on this challenge. These include the LHCb experiment, which started collecting new data when the LHC began its most recent run this summer. The Belle II experiment in Japan, which is dedicated to investigating B meson decays, is also gathering new evidence. If just one of these anomalies were confirmed, it would prove the existence of new particles or interactions. Furthermore, it would mean that the new particles must have masses that could be probed directly at the LHC or a future collider. These novel particles would also affect other phenomena we can observe, allowing physicists to make complementary tests of the new particles' properties.

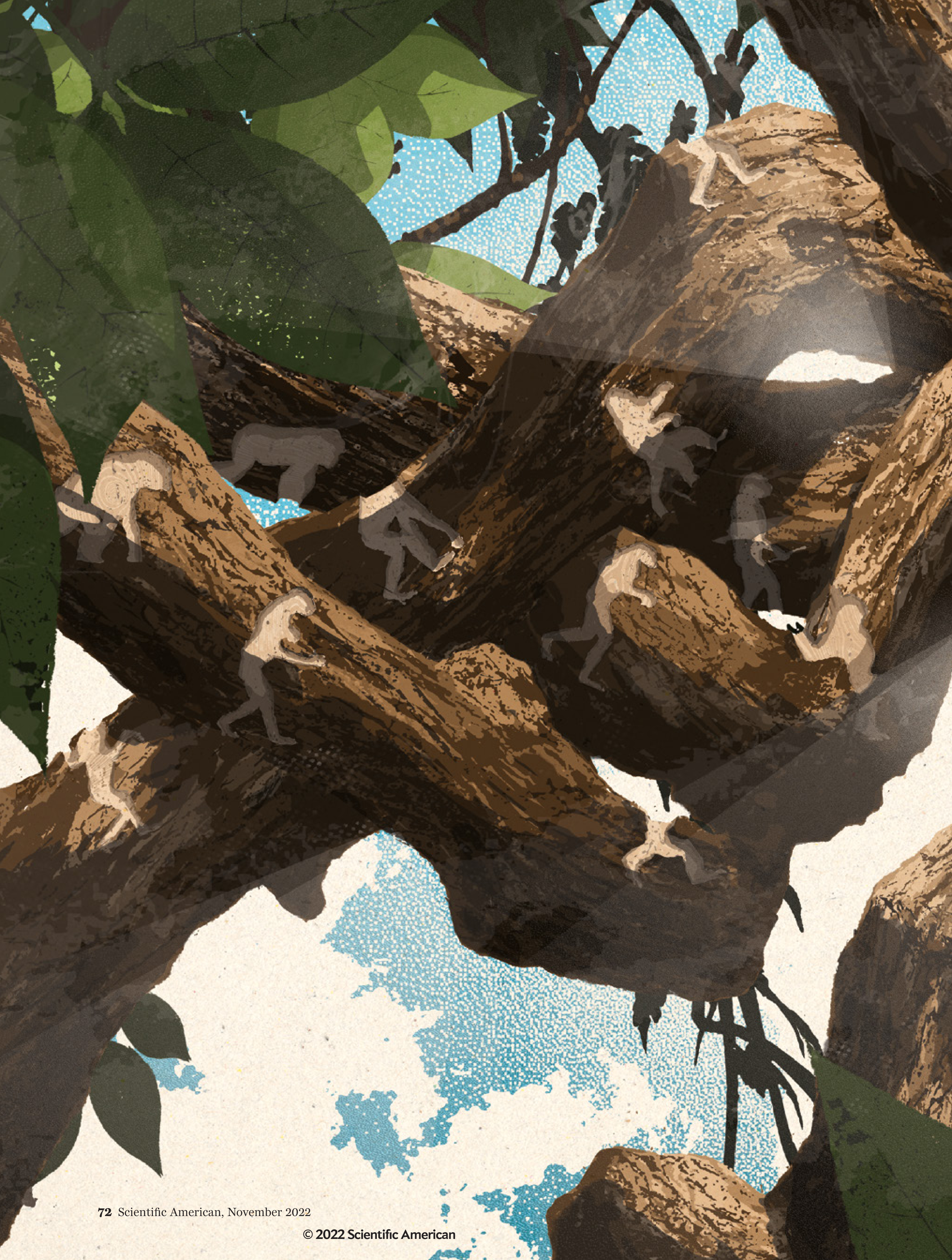
Future accelerators could provide further insights. An electron-positron collider, such as the Future Circular Collider (FCC-ee) planned at CERN or the Circular Electron Positron Collider (CEPC) to be built in China, should have a sufficiently high luminosity (meaning they produce enough collisions) to create large numbers of *Z* bosons. These are useful for observing predicted deviations from the Standard Model in several ways. First, most anomalies, in particular the anomalous magnetic moment of the muon, would affect *Z* decays, such as *Z* bosons turning into a muon and an antimatter muon. Second, the *Z* bosons expected at the FCC-ee would produce an unprecedented number of beauty quarks and tau leptons. Large numbers of these particles would allow for precise tests of the decay processes for which we expect to see effects from new particles—effects that are currently not detectable because we lack enough data to see a strong signal. An electron-positron collider could start operating around 2040. Later, physicists hope to collide protons in the same tunnel (the machine would then be called the FCC-hh), producing much higher energies and potentially creating the particles directly. Such a collider would probably not open before 2060, however. I would need a very healthy lifestyle to see one of the models I've worked on confirmed.

We are at an exciting point in this exploration. Results are constantly being updated and questioned. Very recently new theory calculations bolstered the case for new physics in $b \rightarrow s l^+ l^-$ and $b \rightarrow c l \nu$ decays; meanwhile, there are rumors about the reliability of the corresponding experimental measurements. We are all eagerly awaiting updated measurements and further improved theoretical predictions. If the present hints of lepton universality violation hold up, they could provide long-sought guidance toward a more complete fundamental theory of particle physics. We hope such a theory will finally resolve some of our biggest questions about nature—neutrino masses, dark matter and the missing antimatter in our universe. SA

FROM OUR ARCHIVES

Measuring Beauty. Guy Wilkinson; November 2017.
The Unseen Universe. Marcela Carena; October 2021.

scientificamerican.com/magazine/sa



Walks of Life

Mounting fossil evidence is upending the conventional wisdom about the evolution of human bipedalism

By Jeremy DeSilva

Illustration by Mark Smith

LONG BEFORE OUR ANCESTORS EVOLVED large brains and language, even before they tamed fire or made stone tools, they started doing something no mammal had done before: walking on two legs. Skeletal adaptations for traveling upright are evident in fossils of the very oldest hominins—members of the human family—which date to between seven million and five million years ago. Moving on two legs rather than four set the stage for subsequent evolutionary changes in our lineage. It allowed our predecessors to expand their home ranges and diversify their diets, and it transformed the way we give birth and parent our children. This peculiar mode of locomotion was foundational to virtually all the other characteristics that make humans unique.

In the iconic representation of human evolution, a procession of ancestors starting with a chimplike creature ambling on all fours gives way to a series of ever more erect forebears, culminating in a fully upright *Homo sapiens* striding triumphantly on two legs. First popularized in the 1960s, the March of Progress, as this image and its variants are known, has decorated countless books, T-shirts, bumper stickers and coffee mugs.

But paleoanthropological discoveries made over the past two decades are forcing scientists to redraw this traditional, linear imagery. We now know that various hominin species living in different environments throughout Africa, sometimes contemporaneously, evolved different ways to walk on two legs. The emergence of bipedalism kicked off a long phase of rampant evolutionary riffing on this form of locomotion. Our modern stride was not predetermined, with each successive ancestor marching closer to a particular end goal (evolution has no plans, after all). Rather it's one of many forms of upright walking that early hominins tried out—and the version that ultimately prevailed.

MYSTERIOUS FOOTPRINTS

THEY DIDN'T WANT TO GET HIT by a flying lump of elephant poop. Who would? So paleontologists Kay Behrensmeyer

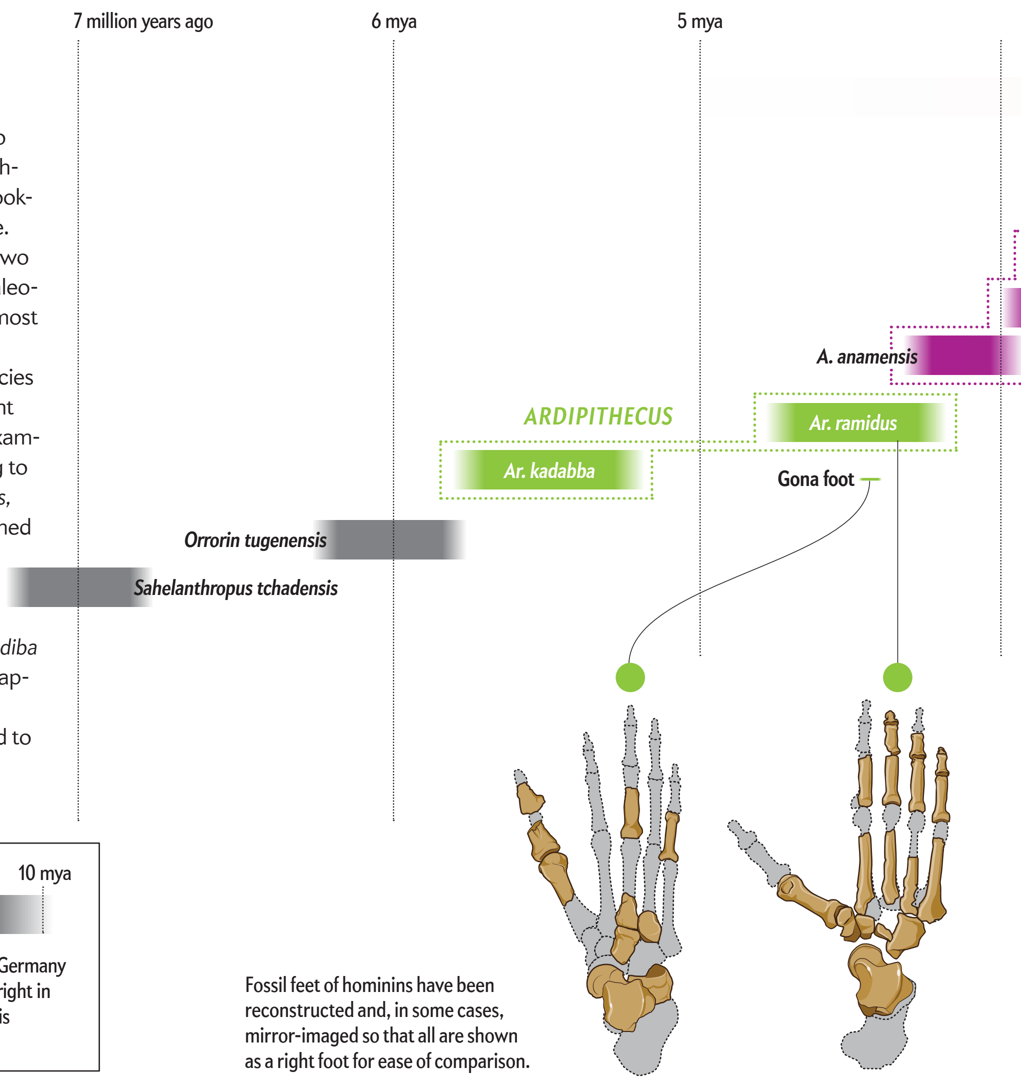
Jeremy DeSilva is a paleoanthropologist at Dartmouth College. His research focuses on the evolution of bipedalism. He is author of *First Steps: How Upright Walking Made Us Human* (HarperCollins, 2021).

FOSSIL FOOTPRINTS from Laetoli, Tanzania, show that two different hominin species walked bipedally in this area 3.66 million years ago. The Site G trackway (*right*) is thought to have been made by *Australopithecus afarensis.* The Site A trackway (*left*) was made by a different, as yet unidentified hominin.

Jeremy DeSilva (*left*); John Reader/Science Source (*right*)

Walk These Ways

Upright walking was long thought to have evolved in linear, sequential fashion, with each successive ancestor looking more like us in posture and stride. But discoveries made over the past two decades have upended that view. Paleoanthropologists now know that for most of the time over which humans have been evolving, multiple hominin species with different ways of walking upright overlapped in time and space. For example, three hominin species belonging to three different genera—*Paranthropus, Australopithecus* and *Homo*—all roamed South Africa's Cradle of Humankind region two million years ago, each with a distinct gait. Some hominins, such as *Australopithecus sediba* and *Homo naledi,* even possessed adaptations to life in the trees long after other hominins were fully committed to life on the ground.



Fossil feet of hominins have been reconstructed and, in some cases, mirror-imaged so that all are shown as a right foot for ease of comparison.

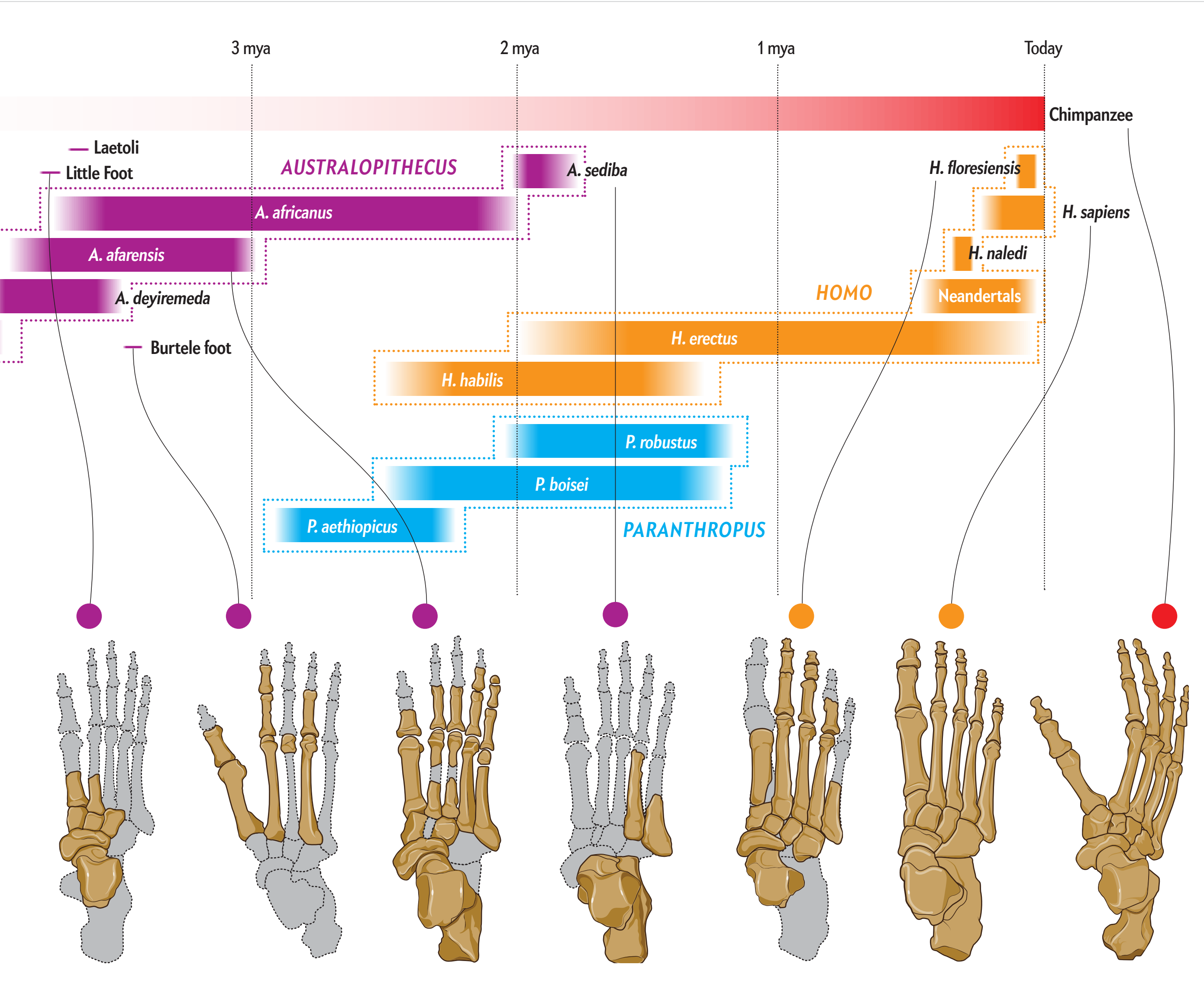
Danuvius guggenmosi, an ape that lived in Germany 11.6 million years ago, may have walked upright in trees. Exactly how it is related to hominins is unknown, however.

and Andrew Hill, who were visiting archaeologist Mary Leakey's fossil site of Laetoli in Tanzania, hopped into a gully to take cover and gather more ammunition for the game of elephant dung dodgeball that had spontaneously broken out. It was July 24, 1976, the day of one of the most serendipitous discoveries in the history of paleoanthropology.

Hill and Behrensmeyer scanned the ground for dung but instead spotted fossilized elephant footprints and raindrop impressions hardened in an exposed layer of volcanic ash that fell 3.66 million years ago. A truce was called in the dung fight, and the others came to marvel at what had been found. Fossils speak broadly about an organism; fossil footprints capture precious snapshots of moments in time for long-extinct animals.

For the next few weeks Leakey and her team explored an area they called Site A, brushing aside overlying sediment to reveal thousands of footprints, mostly made by small antelopes and hares but also from ancient elephants, rhinoceroses, giraffes, large cats, birds and even a beetle. Hoping to find hominins in the mix, Leakey told the group to be on the lookout for bipedal footprints. Maybe they'd get lucky. That September they did. Peter Jones and Philip Leakey discovered five consecutive footprints made by something traveling on two, rather than four, legs. A hominin? Maybe, but the footprints were strangely shaped, and whatever made them had cross-stepped, moving the left foot over the right like a model on a runway rather than walking in the usual human way. The Site A bipedal trackway was a mystery.

Two years later two other members of Leakey's team, Paul Abell and Ndibo Mbuika, discovered another bipedal trackway two kilometers west of Site A at a location dubbed Site G. Two or three, perhaps even four, individuals had walked stride for stride through the muddy ash, leaving 69 stunningly humanlike footprints.



Most scholars agree these tracks were made by *Australopithecus afarensis*—Lucy's species—fossils of which have been found at Laetoli. The Site G tracks were decidedly different from the ones at Site A, however. If a hominin made the tracks at Site G, then what kind of creature made the bipedal trackway at Site A?

In the mid-1980s University of Chicago anthropologist Russ Tuttle took a crack at solving this mystery. After comparing the shape of the Site A footprints with those made by unshod humans, chimpanzees, and circus bears trained to walk on two legs, Tuttle concluded that the prints were either made by a second species of hominin that roamed Laetoli during the Pliocene epoch or made by a bipedally walking bear. Perhaps because a linear view of the evolution of human bipedalism was the dominant paradigm, other researchers embraced the bear hypothesis. As a result, whereas the Site G hominin footprints were exhaustively studied and became world-famous, the footprints at Site A fell into obscurity. Three decades passed before anyone focused on them again.

Dartmouth College, where I teach anthropology, is a small liberal arts school in New Hampshire nestled in a valley between that state's White Mountains and the Green Mountains of Vermont. Although the school is only two hours by car from metro Boston, its motto is *vox clamantis in deserto,* which translates to "a voice crying out in the wilderness." Large swaths of sugar maples provide an ample supply of syrup, the famous Appalachian Trail abuts the campus, and bears—a lot of bears—live in the surrounding woods.

In 2017 my then graduate student Ellison McNutt, who is now a professor of anatomy at Ohio University, and I teamed up with local black bear expert Ben Kilham to collect footprints from cubs whose feet were similar in size to the tracks at Laetoli Site A. Using maple syrup and applesauce to tempt them, we persuaded

Graphic by Dino Pulerà (foot illustrations) and Jen Christiansen

COMPARED WITH the Laetoli Site G footprint (*left*), presumably made by *A. afarensis,* the Site A print (*right*) is short and wide; the big toe sticks out to the side.

John Reader/Science Source (*left*); Jeremy DeSilva (*right*)

the young bears to rear up on their hind legs and amble through an experimental trackway filled with mud. To our surprise, their footprints and gait mechanics were no match for Site A. Bears' heel impressions are narrow, and their steps are widely spaced because their hip and knee anatomy causes them to wobble back and forth when walking bipedally. We started to have our doubts about the bear hypothesis.

More than 40 years have passed since the discovery of the Site A trackway. In that time, seasonal rains have slowly washed sediment from the barren hills at Laetoli, exposing tens of thousands of fossils. Teams led by Charles Musiba of the University of Colorado Denver, Terry Harrison of New York University and Denise Su of Arizona State University have recovered many of these fossils. We know from other sites that an extinct bear called *Agriotherium* did roam Africa during the Pliocene, but not one of the animal fossils these teams have recovered at Laetoli is from a bear. Someone needed to take another look at the bipedal tracks at Site A. But those same seasonal rains that gift us fossil bones and footprints also have the erosive power to take them away. We had assumed the Site A bipedal footprints were long gone. Thankfully, we were wrong.

In 2019 Musiba and I traveled to Laetoli and used Mary Leakey's detailed drawings like a treasure map to identify the precise location where the mysterious bipedal footprints should be. Then we began to dig. After several days Tanzanian team member Kallisti Fabian called to us, "*Mtu*"—the Swahili word for "human." He had found the footprints. The rains had not destroyed them but had covered and preserved all five of them with a layer of fine sediment. Using tongue depressors and thick-bristled brushes, we fully cleaned the prints, revealing never before seen details of the toe impressions, which we captured with high-resolution, 3-D laser scans unavailable to our colleagues working in the 1970s. The heel impressions of the Site A footprints are large, and the big toe is the dominant digit, as it is in humans and our ape cousins. This was no bear. A hominin made these tracks. But which hominin?

Walk on a sandy beach, and you are sure to see a variety of *H. sapiens* footprints—small, flat prints made by a toddler next to the long, arched prints of her mother, for instance. Modern humans come in all shapes and sizes, and so do our feet. Almost certainly, the same was also true for *A. afarensis.* Maybe the footprints at Sites A and G were showing normal variation within a single species of hominin. If so, the small size of the Site A footprints might indicate they were made by a child of Lucy's species. That's what I originally hypothesized, anyway.

Footprint expert Kevin Hatala of Chatham University, who helped to discover and analyze 1.55-million-year-old *Homo erectus* footprints at Ileret, Kenya, joined our team, and together we compared the shape of the Site A footprints with the best-preserved footprints from Site G and another trackway discovered in 2015 at Site S, along with hundreds of footprints made by humans and chimpanzees. The differences we observed did not fit within the range of variation among footprints from people of all ages today.

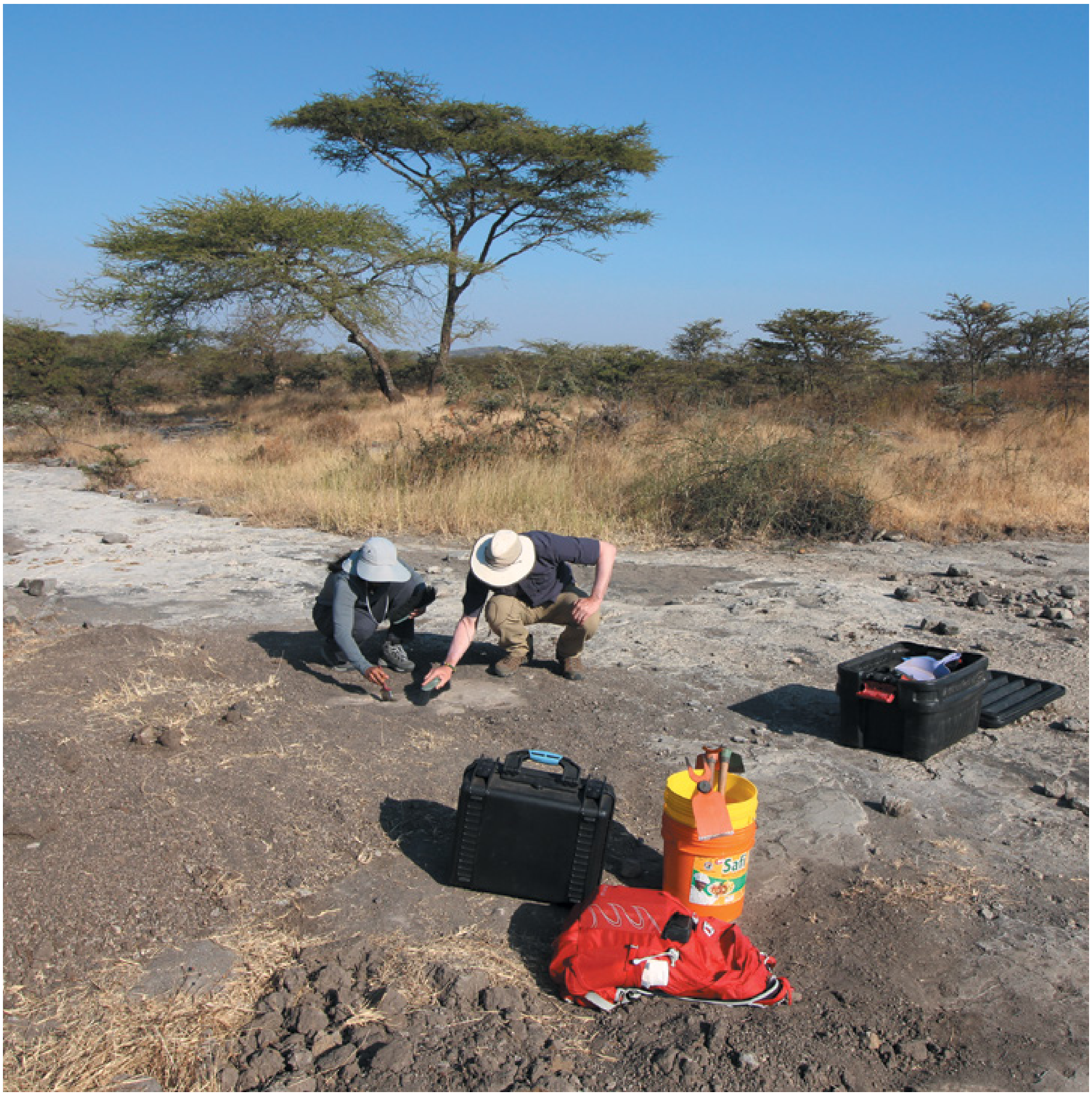
We found that the Site A footprints had a shape that was as different from the Site G and S prints as a chimpanzee's footprints are from yours and mine. That's not to say the Site A footprints were just like a chimpanzee's, only that they were very different in shape from those of Lucy's species. Compared with those presumed *A. afarensis* footprints at Sites G and S, the Site A footprints were short and wide, the big toe stuck out to the side a bit, and there was some evidence the walkers had a more flexible middle portion of the foot.

In our paper describing these findings, published last December in the journal *Nature,* we claimed that not only were the Site A footprints from a hominin, but they also were evidence of a second species at Laetoli. As is expected in science, not all of our colleagues have fully embraced our interpretation. Some think we just found another *A. afarensis* footprint trail. But it is worth repeating that the Site A footprints were so different from the Site G *Australopithecus* prints that our field was convinced for decades that they were made by a bear.

It seems to me that shortly after ash fell from the sky 3.66 million years ago, two kinds of hominins, walking on slightly different feet in slightly different ways, moved north toward the Olduvai Basin in Tanzania, perhaps in search of water. Because it is thought that the footprint layer at Laetoli captures at most a few days of activity, this is the best evidence we have that different Pliocene hominin species not only were contemporaries but shared the same landscape. How they interacted—if at all—is anyone's guess at this point.

FOSSIL FEET

THE REDISCOVERY OF THE LAETOLI SITE A footprints and our conclusion that they were made by a second species are the latest additions to a growing body of evidence that the evolution of upright walking was a lot less linear, more complex and more interesting than we once thought. The other evidence comes not from footprints



DECADES AFTER the discovery of the Site A tracks at Laetoli, researchers returned to study the tracks again. Although seasonal rains tend to erode footprints, in this case they covered them with a protective layer of sediment.

Shirley Rubin

but from fossils of the hominins themselves. Isolated foot bones are rare in the human fossil record, and foot skeletons are even more elusive. So it is exciting that in the past two decades, paleoanthropologists searching in Africa's Great Rift Valley and in caves in South Africa have quadrupled the number of fossils from the only part of a biped's body usually in direct contact with the ground. Many of these new discoveries sample a pivotal period in human evolution, between five million and three million years ago, when our ancestors were becoming committed upright walkers. In 2017 McNutt and I teamed up with Bernhard Zipfel, a former podiatrist-turned paleoanthropologist at the University of the Witwatersrand in South Africa, to make sense of these finds.

Specifically, we sought to evaluate the received wisdom about the evolution of bipedalism in light of the new fossil evidence. According to the traditional view, hominins started out with a chimplike foot built for grasping tree branches. This foot evolved into a transitional foot capable of both grasping and walking, as seen in the fossil known as Ardi, a member of *Ardipithecus ramidus* that lived in Aramis, Ethiopia, 4.4 million years ago. Fast forward to Lucy, the *A. afarensis* individual who lived in Hadar, Ethiopia, some 3.2 million years ago, whose foot has a big heel and a stiff midfoot that were better adapted to life on the ground. With the emergence of our own genus, *Homo,* roughly a million years later, the foot became even better suited to terrestrial locomotion, evolving shorter toes and a high arch.

After studying all the foot fossils carefully curated in museums throughout Africa, we noticed a very different pattern emerging from our data. As bipedalism evolved in our earliest ancestors, there was a burst of evolutionary experimentation that resulted in different hominins having different foot forms. We identified five different foot morphs, possibly indicating five distinct ways of walking upright, in the two-million-year interval we studied. Between the chronological bookends of Ardi and Lucy are three other uniquely shaped feet. The first belongs to an Ardi-type creature, about the same

MULTIPLE STYLES of upright walking continued to evolve even after the emergence of species with our modern human gait. *Australopithecus sediba* (*left*) had adaptations to both terrestrial and arboreal locomotion; tiny *Homo floresiensis* (*right*) had large, flat feet that might have required taking small, high steps.

S. Entressangle and Elisabeth Daynes/Science Source (*left*); Sebastien Plailly and Elisabeth Daynes/Science Source (*right*)

age as that fossil, from Gona, Ethiopia; the second comes from a 3.67-million-year-old hominin from Sterkfontein, South Africa, dubbed "Little Foot"; and the third is a strikingly primitive foot from a site called Burtele in Woranso-Mille, Ethiopia, that dates to 3.4 million years ago. Although all five of these hominin feet exhibit both apelike and humanlike features, these traits occur in a completely different combination in each foot and do not follow the predicted pattern of becoming less apelike and more humanlike over time.

Like an ancient version of the story of Cinderella, perhaps one of these recently discovered feet will fit the mysterious hominin footprints at Laetoli Site A and reveal the identity of the track maker. We'll see as we continue to explore these early stages of our evolutionary history.

SUSTAINED DIVERSITY

INTRIGUINGLY, THE PATTERN of locomotor diversity is not limited to these early chapters of human evolution. Take, for instance, *Australopithecus sediba*. Rivaling the elephant dung fight in the lore of fortuitous paleoanthropological discoveries, this nearly two-million-year-old hominin was discovered in 2008 by then nine-year-old Matthew Berger. He literally stumbled over a rock containing a hominin clavicle and lower jaw while surveying for fossils at the site of Malapa Cave in South Africa's Cradle of Humankind with his father, paleoanthropologist Lee Berger of the University of the Witwatersrand. In the months that followed, Berger and his team excavated the fossil-bearing cave walls and discovered two partial skeletons of a new species they called *A. sediba*. Berger invited me to study the foot and leg fossils shortly after I had completed my Ph.D.

I was shocked by what I saw. The shapes of the bones were all wrong. For a hominin of this time period, the heel bone was too apelike, and the midfoot, ankle, knee, hip and lower back showed strange traits in both skeletons. In isolation, these bones were bizarre. But in concert, they told the story of a hominin with a peculiar way of walking, one that was similar to that of humans today who hyperpronate, or excessively transfer weight to the inside of their foot. This gait can lead to joint pathologies in modern people, but Berger and I and our colleagues interpreted the peculiarly shaped bones of *A. sediba* as anatomical solutions to the problems modern humans face when they walk in this manner. In other words, we think this species was adapted to walk in this way. Why? The shoulders and arms of *A. sediba* indicate that it climbed trees, and its teeth preserve microscopic traces of plant cells derived from leaves, fruit and bark—evidence that this species frequently fed in trees. This way of walking was the compromise for a hominin well adapted for life in two worlds, navigating between the trees and the ground—long after other hominin species had fully committed to terrestrial life.

A. sediba was not the only hominin walking around southern Africa two million years ago. In 2020 a team of researchers led by Andy Herries of La Trobe University in Australia reported newly discovered fossils from the Drimolen Cave system, also in the Cradle of Humankind area. These fossils came from two other hominin species: the large-toothed *Paranthropus robustus* and the much more humanlike *H. erectus*. In other words, three different kinds of hominins from three different genera—*Homo, Paranthropus* and *Australopithecus*—were coexisting.

We know from a partial skeleton discovered in the 1980s along the western side of Lake Turkana in Kenya that *H. erectus* had a body form nearly identical to that of humans living today. Footprints on the eastern side of the lake confirm that these hominins walked like us. *H. erectus*—the likely ancestor to the lineage that led to our own species, *H. sapiens*—would have peered across its territory and seen two other bipeds from two different genera, *Australopithecus* and *Paranthropus*. Given the different shapes of their foot and leg bones, I think these hominins all had different styles of walking.

The pattern of diverse walking styles persisted even after *Australopithecus* and *Paranthropus* went extinct. As recently as 60,000 years ago, by which point *H. sapiens* was well established, the small human species *Homo floresiensis*, nicknamed the Hobbit, roamed its island home of Flores in Indonesia on relatively giant, flat feet and short legs with small joints. I wonder if the resulting gait would include the short steps and high knee drive of a person in snowshoes.

Perhaps gait differences helped hominins determine whether a group foraging in the distance belonged to their own species or another. And if gait did reveal the distant foragers to be from their same species, could the observers tell whether the other individuals were friends and family or strangers? Knowing the answer could have been the difference between avoiding conflict and inviting it. Gait, it turns out, is more than a means of getting from point A to point B.

OPEN QUESTIONS

MANY QUESTIONS REMAIN about the evolution of bipedalism. We still do not know why upright walking was selectively advantageous for our earliest ancestors and extinct relatives. Hypotheses abound. In 1809 French naturalist Jean-Baptiste Lamarck speculated that humans evolved upright walking to see over tall grass. Six decades later Charles Darwin surmised that walking on two legs freed the hands to use tools. Other scholars have since proposed that it allowed our ancestors to gather and carry food or to wade through shallow water. Still others argue that it offered a more energetically efficient means of traveling between scattered resources. It seems to me, though, that efforts to identify *the* reason bipedalism evolved are a fool's errand. Instead I think it's possible—maybe even probable—that bipedalism evolved multiple times at the base of the hominin family tree, perhaps for different reasons, in different hominins living in slightly different environments throughout Africa. The diversity of foot forms found in Pliocene fossil sites across the continent supports such a scenario.

The fossil record of apes from the Miocene epoch (23 million to 5.3 million years ago) highlights other unknowns. Paleoanthropologists working in Africa have struggled to find ape fossils from this all-important time period when hominins diverged from other apes. But their counterparts in southern Europe have turned up an impressive collection of bones from apes that used to live in Spain, France, Germany, Greece, Italy, Hungary and Turkey. Judging from their hands, arms, backs, hips and legs, these European apes didn't knuckle-walk like a chimpanzee. Instead some of them may have been able to move on two legs more often and more efficiently than modern African apes do. Depending on where these ancient apes—such as the 11.6-million-year-old *Danuvius guggenmosi* from Germany, first announced in 2019—fit into the family tree, it is even possible that the ape from which the ancestors of humans, chimpanzees and gorillas split was not a knuckle-walker at all but more upright, using hand-assisted bipedalism to "walk" through the trees. In that case, the unique hominin adaptation would be not bipedal walking per se but rather bipedal walking *on the ground*. If more fossils continue to support this hypothesis, then rudimentary bipedalism might turn out not to be a new form of locomotion at all; it may be an old one co-opted for a new environment as our ancestors shifted from an arboreal to a terrestrial existence.

This idea is controversial and in need of further testing. The challenge is that paleoanthropologists have yet to unearth fossil foot or leg bones from Africa during the key time period when the lineages that would eventually lead to humans, chimpanzees and gorillas were beginning to diverge, between 12 million and seven million years ago. To fill in that gap, we rely on the anatomy of those ancient apes from southern Europe. In a way, it is like trying to figure out what your great-grandmother looked like by studying tattered black-and-white photographs of your 19th-century cousins three times removed. They'll provide some clues but not the full picture. We'll see how this hypothesis holds up in the decades to come as more fossils are recovered from sites around the Mediterranean and in Africa. For now, though, the very beginnings of upright walking remain shrouded in mystery.

Once our ancestors got moving on two legs, they kept on walking, and that journey has continued right up to today. In a lifetime, the average person will take about 150 million steps—enough to circle Earth three times. We stroll, stride, plod, traipse, amble, saunter, shuffle, tiptoe, lumber, tromp, lope, strut and swagger. After walking all over someone, we might be asked to walk a mile in their shoes. Heroes walk on water, and geniuses are walking encyclopedias. But rarely do we humans *think* about walking. It has become, you might say, pedestrian. The fossils, however, reveal something else entirely. Walking is anything but ordinary. Instead it is a complex, convoluted evolutionary experiment that began with humble apes taking their first steps in Miocene forests and eventually set hominins on a path around the world. SA

FROM OUR ARCHIVES

The Origin of Us. Kate Wong; September 2020.

scientificamerican.com/magazine/sa

In Schools, Talk about Racism Can Reduce Bias

New laws prohibit these conversations, but dialogue dispels bias and distress

By Camilla Mutoni Griffiths and Nicky Sullivan

"Where are the Native Americans now?" asked fifth grade students in an Iowa City classroom last year. There are many ways their teacher, Melanie Hester, might have answered. She could have pointed out that today Native Americans live in cities and towns across the U.S. About 20 percent live on reservations, and Hester could have used that to open a discussion of the U.S. government's forcible movement and isolation of tribes. Hester might have also discussed how European and American settlers brutally killed many Native Americans in the 18th and 19th centuries.

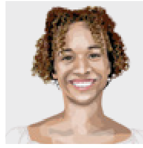
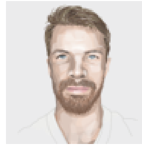
Instead she evaded the question and continued her lesson without offering historical context for her students to understand the present. Teachers across the country are avoiding explicit conversations about race, racism and racial inequality because of a series of recent laws passed in several states. In Iowa, for example, a law prohibits any teaching that suggests the U.S. is "fundamentally or systematically racist or sexist." The Iowa law also specifies that teachers must ensure that no student feels "discomfort, guilt, anguish or any other form of psychological distress on account of that individual's race or sex." The laws in other states lay out similar logic.

The legal language seems, for the most part, protective of children. But the effect is quite the opposite. As psychologists who study how parents and teachers communicate with kids about race, we can attest to an ever growing body of scientific evidence that suggests these laws are failing the children they purport to help.

First, years of research make it evident that kids notice racial and ethnic disparities from an early age. For example, psychologists have found that white kids as young as age four will consistently pair white families with higher-wealth items (such as nice cars and bigger houses) and Black families with lower-wealth items (for instance, run-down cars and smaller houses). In other words, very young children are aware of persistent racial disparities in wealth. Around the same age, children begin forming preferences for wealthier kids with more "stuff," which, given the link between wealth and racial background in the U.S., may result in white children preferring and choosing to play with other white peers over Black peers.

Second, we know that when children notice differences between people or groups, they usually look for an explanation. Here a psychological principle called the inherence bias comes into play. In general, when we see someone behave in a distinctly different way from others, we assume there is something inherently different about that person. Adults often fall into this trap: if someone cuts you off on the highway, you are likely to assume they are a bad driver rather than assume, for instance, that they are a good driver who happens to be rushing to a hospital in an emergency. In the same way, children are more likely to attribute a wealth difference between communities to the groups' capabilities or intelligence rather than something external, such as a historical advantage one group has had over another. Children often go one step further and think that groups are biologically or innately different. These attitudes are what psychologists call essentialist beliefs because

Illustration by Vanessa Brantley-Newton

Camilla Mutoni Griffiths is a social psychologist at Stanford University. She studies how our interactions with American institutions contribute to racial attitudes and biases.
Nicky Sullivan is a Ph.D. student in developmental and social psychology at Stanford.

they attribute group differences to some deep, underlying and often unknown "essence."

These tendencies toward inherence and essentialism are especially harmful when we think about children's efforts to understand racial disparities. Scientists agree that race is not biological. It is not inherent or innate. Instead race is the product of social and cultural ideas that are imposed on groups of people. These ideas become codified in our institutions and in the ways that we interact with one another, thus producing the inequalities we see in the world.

This means that children need *external* explanations, such as historical injustices and racial discrimination, to understand the differences between groups that they are observing. Without that context, children can mistakenly believe that racial difference is inherent, which leaves them with an inaccurate understanding of the world. More concerning, these beliefs about the inherent or essential nature of racial difference are actually a foundation of racial bias. In fact, multiple studies have found that when kids have more essentialist beliefs about race, they also hold more stereotypes about other racial groups.

State laws claim to protect kids from forming racist beliefs, but research suggests they are more likely to do the opposite.

In other words, without explicit discussions about race and the external, rather than internal, causes of racial disparities, children will come to the wrong conclusions and may develop racial biases. In principle, these problems could apply to any child who is not given greater context for racial differences. White children may be especially at risk because they are often the least likely to have conversations about racism with their families. In fact, one of us (Sullivan) tracked almost 1,000 parents in 2020 and found that white Americans were significantly less likely to talk to their children about race than Black Americans, even after the much publicized murder of George Floyd prompted national protests and dialogue about racism.

When we think about new laws limiting discussion of race in schools, it's critical to keep in mind how they will impact children of color specifically. The research we've discussed suggests that students will be more likely to develop racially biased views in the absence of explicit lessons. As a result, children of color are likely to face more discrimination, not less. This outcome is clearly at odds with the language of the laws, which explicitly state that children should not be made to feel psychological distress because of their race. Yet that is precisely what will happen if children of color face more discrimination.

In contrast, explicit conversations with kids about racial disparities can help reduce some of the negative consequences we have described. In one study, white elementary school students who received history lessons about racial discrimination faced by Black people had more positive views of Black people and were less likely to hold stereotypes than students who didn't receive such lessons. And those lessons did not lead either white or Black children to hold more negative views of white Americans, which is a commonly voiced concern among those who oppose teaching about racism. There is also early evidence from a preprint paper (which has not yet been through peer review) that when parents engage in honest, accurate conversations about race with their children, it can decrease kids' racial biases.

The laws passed in Iowa and elsewhere claim to protect kids from forming racist beliefs, but the research suggests they are more likely to do the opposite. When it comes to children's understanding of racism and the development of racist beliefs, the biggest danger isn't teaching or talking to children about these topics—it's staying quiet. SA

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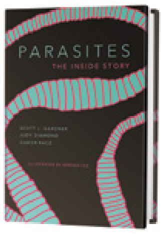
NONFICTION

Homage to the Bloodsuckers

A crash course in the overlooked world of parasites

Review by Rachel Nuwer



Parasites: The Inside Story
by Scott L. Gardner, Judy Diamond and Gabor Rácz. Illustrated by Brenda Lee. Princeton University Press, 2022 ($29.95)

Growing up on a farm in Oregon's Willamette Valley, Scott L. Gardner would comb the rolling hills for carcasses of mice, pheasants and other expired wildlife. It was not those larger animals that intrigued the young naturalist, though, but the smaller life-forms nestled inside their organs and flesh. Gardner was after their parasites.

Gardner's uncle, Robert L. Rausch, was a leading parasitologist with a career spanning more than 60 years. Gardner would regularly mail coiled worms, tear-shaped flukes and other specimens he found in his dissections to his uncle for identification help. One of them—a tapeworm Gardner fished out of a camas pocket gopher—turned out to be a species new to science. He later named it *Hymenolepis tualatinensis,* after the Tualatin River where he'd discovered it.

Gardner was hooked, so to speak. He went on to become a parasitologist at the University of Nebraska–Lincoln, where he also serves as curator of the Harold W. Manter Laboratory of Parasitology, one of largest parasitology collections in the world. In *Parasites: The Inside Story,* which Gardner co-authored with his colleagues Judy Diamond and Gabor Rácz, he shares the story of *H. tualatinensis* to make a larger point about parasites: these species are all around us yet woefully understudied. More and more, though, scientists are learning that parasites are facing the same survival pressures as free-living animals, including climate change, habitat loss and other anthropogenic stressors. Indeed, around his family's farm today, the tapeworm he discovered just a few decades ago "is nowhere to be found."

Disappearances of parasitic species such as *H. tualatinensis* are much more likely to go unnoticed than declines of songbirds or butterflies. Parasites are grossly overlooked by scientists and the public alike and, when acknowledged at all, are usually singled out only as agents of disease and death. Yet as the authors point out, our understanding of nature is glaringly incomplete without an understanding of parasites.

These "unseen influencers" affect virtually every other species on the planet and create complex communities within every environment—communities that ultimately drive the ecology of those systems. Parasites, they assert, form "the scaffolding for all interactions among organisms."

Parasites provides a crash course on just how ubiquitous those interactions are. The authors describe parasitoid wasps that lay their eggs inside the cocoons of other parasitoid wasps, for example, and leeches that spend their entire lives inside the anuses of hippopotamuses. Parasites also seem to have found their way to every inch of the planet, from the dry valleys of Antarctica to the highest levels of the atmosphere, where they are sometimes blown. Ecologists increasingly agree that parasites play as strong a role in shaping ecosystems as predators do.

Parasites may require up to five hosts to get from egg to larva to adult, and one of the most delightful parts of *Parasites* includes the 11 figures—mini comics, really—from illustrator Brenda Lee. Each one depicts a different parasite's life cycle, from the human roundworm's beginnings as an egg in a pile of curled feces to the prolific expulsion of tapeworm end segments from the rectum of a sperm whale that explode into millions of eggs. Outside the whale these eggs are eaten by zooplankton, where they hatch into larvae. Infected zooplankton are in turn eaten by fish that are eaten by whales, beginning the cycle all over again.

In spite of this co-dependent lifestyle, parasites can be opportunistically nimble, "switching hosts over time as possibilities for new colonization become available," as Gardner and his colleagues write. Tapeworms, for example, survived the most recent asteroid impact that took out three quarters of all life on Earth by jumping from marine-based hosts to seabirds. Yet co-dependence can also make parasites vulnerable. If a parasitic species' host suddenly goes extinct—or if conditions change precipitously—the parasites may disappear, too.

Parasites works best when it delves into the details of these surprising life histories and the evolution behind them. As a primer on the subject, it was a zippy read. But I would have enjoyed more firsthand narration of the authors' experiences. Anecdotes such as Gardner's boyhood discovery of the tapeworm *H. tualatinensis* are shared in the third person, which means readers are left to wonder how Gardner felt when he realized he had found a new species—and what his reaction was when it dawned on him that the species had vanished.

Gardner and his co-authors do not explain what caused the disappearance of *H. tualatinensis.* Most likely—as with so many other mysteries surrounding parasites—they simply do not know. They hint that it might have been the victim of "human environment mismanagement," either switching to a new host or disappearing from the region entirely. What the authors can say for certain is that "the imminent loss of parasite diversity will forever curtail our understanding of how entire communities of organisms interact and evolve."

Rachel Nuwer is a freelance journalist and author whose work has appeared in the *New York Times* and *National Geographic.*

Illustration by London Ladd

NONFICTION

Fair Measures

Measurements can be used to advance or exploit

ATU Images/Corbis/Getty Images Plus

Scientific discoveries are often associated with dramatic insights, such as when the proverbial apple fell on Newton's head. But journalist James Vincent, who covers science and technology for *The Verge,* argues that true progress is built inch by inch.

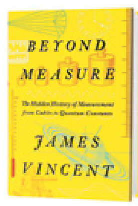
In *Beyond Measure,* Vincent tells the story of metrology by exploring how humanity and measurement have shaped each other throughout history. It's an ambitious project that spans centuries, from ancient Egyptians forecasting feast or famine from the annual depth of the Nile River to the tracking and monetization of our self-measurements online by tech companies such as Google and Facebook.

Vincent masterfully draws significance out of every millimeter. He explains how informal measurements such as the pinch (as in the amount of salt used in cooking) and the cubit (the length from the elbow to the fingertip) highlight an intimate relationship between metrology and our bodies. Later he describes how the French Revolution was in part fostered by the politics surrounding the metric system.

With such a wide scope of topics—including the creation of the first thermometer, Albert A. Michelson's experiments to determine the speed of light, and our modern reality in which human behavior is reduced to a set of statistics such as BMIs in the health-care industry—Vincent has a tendency to jump back and forth in time. This can sometimes make it hard to follow along, but it never sours the reader's curiosity in the rich historical context he provides. The book is filled with wonder and love for a field many of us have wrongly associated with emotionless objectivity.

Beyond Measure especially shines when it portrays the innate messiness of metrology. Vincent does not just tell us that it's difficult to find consensus on how to measure distance; he shows how the field is inextricably linked to nation building, as governments throughout history have used differing appraisals to shortchange farmers or to steal, divide and colonize Indigenous peoples' lands. He also tackles the most sinister uses of the science, such as how statistics was exploited to support eugenics in the late 1800s. In doing so, Vincent crafts a clear-eyed and complex picture of measurement as a tool of both radical social advancement and subjugation—depending on who wields it.

—Michael Welch

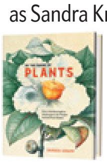


Beyond Measure: The Hidden History of Measurement from Cubits to Quantum Constants
by James Vincent.
W. W. Norton, 2022 ($32.50)

IN BRIEF

In the Name of Plants: From Attenborough to Washington, the People behind Plant Names

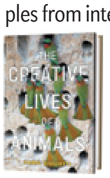
by Sandra Knapp. University of Chicago Press, 2022 ($25)



When Shakespeare asked, "What's in a name?" he probably wasn't expecting as literal an answer as Sandra Knapp's charming biographical compendium, *In the Name of Plants.* Some of these essays, which span both the globe and history, center on legacy figures, such as Darwin and Sequoia. Others are surprising (Lady Gaga has a fern named after her!) or strive to correct historical inaccuracies and erasures. But the book isn't just an elegant reference text. It's a reminder that the methods we use to classify things are inseparable from who we are. *—Sara Batkie*

The Creative Lives of Animals

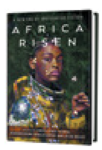
by Carol Gigliotti. NYU Press, 2022 ($30)



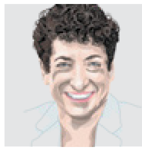
From playfully bowing puppies to seductively singing alligators, Carol Gigliotti combines examples from interviews with scientists and excerpts of previously published books in this delightful index of animal inventiveness. Gigliotti explores animals' intelligence by focusing on their creative approaches to problem-solving—how prairie dogs modify their communication to describe something they've never seen before, for example. Her decades spent teaching the arts to college students sparked her curiosity in the diversity of creativity, inspiring her to write a book that argues "we do not give meaning to the lives of animals; they are able and willing to do that themselves." *—Fionna M. D. Samuels*

Africa Risen: A New Era of Speculative Fiction

edited by Sheree Renée Thomas, Oghenechovwe Donald Ekpeki and Zelda Knight. Tordotcom, 2022 ($27.99)



In *Africa Risen,* bewitching technologies and devastating magic burst forth from Africa and its diaspora in tales of once human androids crumbling in their quest to live forever, mortals scrambling to become gods, and climate disasters. This vibrant anthology—a well-paced feast of today's most thrilling speculative fiction—has 32 short stories penned by Black authors all over the world. With settings from deserts too dry to cry in to virtual realities where anyone can rise to—or topple from—power, *Africa Risen* embraces darkness and struggle as readily as hope and whimsy. *—Sasha Warren*



Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).

Downplaying the Pace of Arctic Warming

Researchers, worried about hype, often think underestimation is good

By Naomi Oreskes

Climate scientists have a surprising habit: They often underplay the climate threat. In 2007 a team led by Stefan Rahmstorf compared actual observations with projections made by theoretical models for three key climate variables: atmospheric carbon dioxide, global average temperature and sea-level rise. While the projections got CO_2 levels right, they were low for real temperature and sea-level rise. In 2008 Roger Pielke, Jr., found that sea-level rise was greater than forecast in two of three prior Intergovernmental Panel on Climate Change reports. In 2009 a review of hundreds of papers on climate change identified several areas where scientists had lowballed event predictions but none in which they had overestimated them.

In 2013 researcher Keynyn Brysse, then at the University of California, San Diego, along with other colleagues and me, pointed out that these underestimates represent a kind of bias. Scientists tended toward lower projections because they did not want to be accused of making dramatic and exaggerated claims. The articles reporting the underestimates have been widely cited, so one might think that by now scientists would have taken corrective steps.

But recent studies of Arctic warming suggest that the problem may not have gone away. For instance, scientists have long known about how Arctic ice reflects sunlight, redirecting heat away from the planet. But as polar ice melts because of global warming, the Arctic Ocean absorbs more heat, which causes the Arctic to warm even more, which melts more ice, and so on. It should surprise no one, then, that the area is warming fast. Yet scientists have been caught off-guard by just how fast the region is heating up.

A recent study led by Mika Rantanen of the Finnish Meteorological Institute found that, since 1979, the Arctic has warmed nearly four times faster than Earth as a whole. Few climate models have predicted an effect this large.

Model results are typically reported as the averages of many runs of a set of similar models, referred to as ensembles. These new Arctic temperature observations are not only warmer than all the major ensemble averages but, in some cases, outside the whole ensemble envelope. In one very large and highly respected one—the Max Planck Institute Grand Ensemble—the observed warming for 1979–2021 is entirely beyond the results. Some real-world observations are hotter than even the hottest projections.

This has several implications. First, it reminds us that averages can be misleading. Extreme outcomes may be unlikely but do occur and are crucial in assessing risk. Second, it suggests that climate models may be continuing to underestimate key climate effects.

Admittedly, the observations might be wrong; measuring the temperature of the region is notoriously difficult, in part because of sparse sensor coverage over the Arctic Ocean. In addition, scientists may have analyzed different time periods or used conflicting definitions of "Arctic" boundaries. But it may also be that their subconscious bias toward playing things down was playing itself up.

We've heard a lot in recent years about subconscious bias in relation to race and gender discrimination. But subconscious bias can be caused by many things, including defensiveness. Even now scientists continue to be accused of exaggerating climate risks by prominent figures who get outsized media attention. Scientists who have internalized this concern may be subconsciously biasing their models to be unrealistically conservative.

If scientists have underestimated Arctic warming, they have likely minimized amounts of permafrost melting and methane release as well. And that could be truly dire because the permafrost holds about 1.5 billion metric tons of organic carbon, twice as much as now in the atmosphere. Were that carbon to be rapidly released, it could cause a worst-case scenario: a runaway greenhouse effect. Whatever the cause, it's time that scientists looked seriously at whether their models continue to underplay critical aspects of the climate problem. Low estimates can create the false impression that we have more time to fix the problem than we actually do. ■

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Illustration by Jay Bendt

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

NOVEMBER

1972 Sunlight on Venus

"Additional knowledge about the cloudy planet Venus has been gathered by the Russian space probe Venus 8, which made a soft landing in July. One of the debates about Venus was whether or not its cloud cover was so thick that sunlight would not penetrate to the surface. Venus 8 carried a photometer that gave readings as the probe parachuted through the atmosphere for nearly an hour before landing. The photometer showed that sunlight is greatly attenuated by the atmosphere, but some sunlight does manage to penetrate to the surface."

1922 Movie Wheels Turn Backwards

"Everyone has noticed at the movies the optical illusion whereby the wheels of an auto appear to turn backwards, while the auto is going forward. The phenomenon is a special case of the 'persistence of image' on which the movies depend. If the wheel revolves at such a rate as to bring each spoke into the position occupied by another spoke in the preceding [frame], the wheel will appear to stand still. If the distance moved is less than half the angular distance between the spokes, the wheel will appear to revolve normally. But if the distance is more than this, say, three-quarters the angular distance between the spokes, then an illusion of backward motion is produced. The eye connects each spoke with the spoke which, in the previous image, was nearest to its present position. If a wheel has spokes differing in shape or color, the eye cannot confound them, and no illusion is produced; the illusion happens only when the spokes are identical."

Made in America, for China

"The intelligent manufacturer in this country realizes that future prosperity lies largely in export trade. Unquestionably China offers an opportunity that is unique. The Republic of China is more than twice as large as the United States, and its population is four times as great. There are practical opportunities in China for the sale of nearly all American commodities."

In 2021 the U.S. trade deficit in goods with China was more than $353 billion.

Regulate Airplanes Like Cars

"The frequency of airplane accidents has had a depressing effect upon the development of commercial aviation. It was not until the public realized that the automobile was reliable and could be controlled by any intelligent person, that the motor car began to make rapid headway. What we need is a law with clauses calling for the periodical inspection of [airplanes], and for the rigid licensing of pilots. Today, anyone who has the money can buy an airplane, fly it, and invite people to go up; and to this situation many of the accidents must be charged. If no one can drive a motor car without a State license, why in the name of common sense should it be possible to engage in the far more difficult practice of aviation, without the slightest governmental control?"

1872 Tattoos Color the Cornea

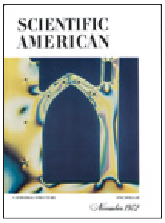
"Dr. R. J. Levis, of the Pennsylvania Hospital, has devised a means of coloring opacities in the cornea. The instrument used is a bundle of from three to six very fine sewing needles. Ordinary water pigments are used, rubbed to a pasty consistence and mixed with a little glycerin. For the black of the pupil, Indian ink is employed. The paint is applied thickly over the opaque spot. The needle points are made to penetrate repeatedly and rapidly in varying directions, until much of the opaque surface is gone over. Two or more repetitions of the process are required. The operation is said to be painless, and as the coloring matter is tattooed into the tissues, it cannot be washed out by tears."

Windmills Galore

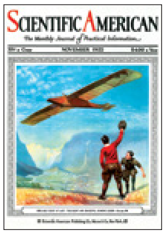
"One hundred and twenty-one patents have been granted on windmills in the United States since 1854."

Mosquito Repellent

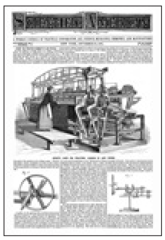
"A. D. Breazele of Alabama has patented a mosquito frightener composed of the following formidable ingredients: Oils of [the plants] pennyroyal, savin, origanum, terebinthe and sassafras; tinctures of lavender, chloroform and arnica; gum camphor, niter [potassium nitrate], alcohol and kerosene oil. If the Alabama mosquitoes can stand such a preparation, the only remaining thing to be done is to set mouse traps to catch them."



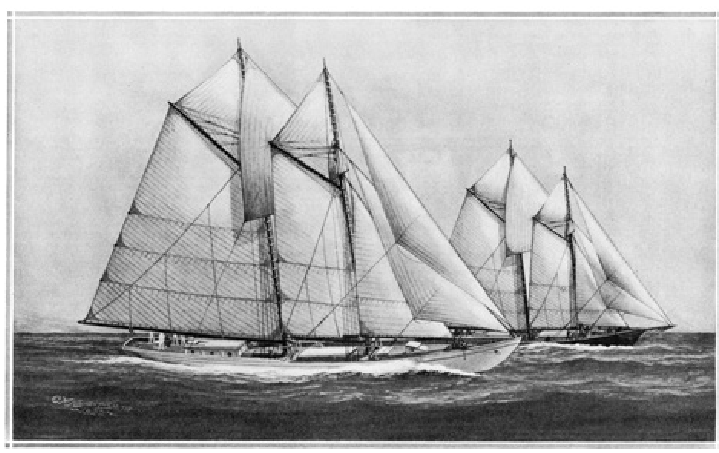
1972



1922



1872



1922, BOAT RACE: "The *Elizabeth Howard* is one entrant for the Fisherman's Cup. High speed is as valuable to the fishing schooner as to the racing yacht; for when these boats have a full catch aboard there is every inducement for them. At least half a dozen of these splendid schooners will compete in the trial races."

Scientific American, Vol. 127, No. 5; November 1922

Text by Andrea Thompson | Graphic by Amanda Montañez

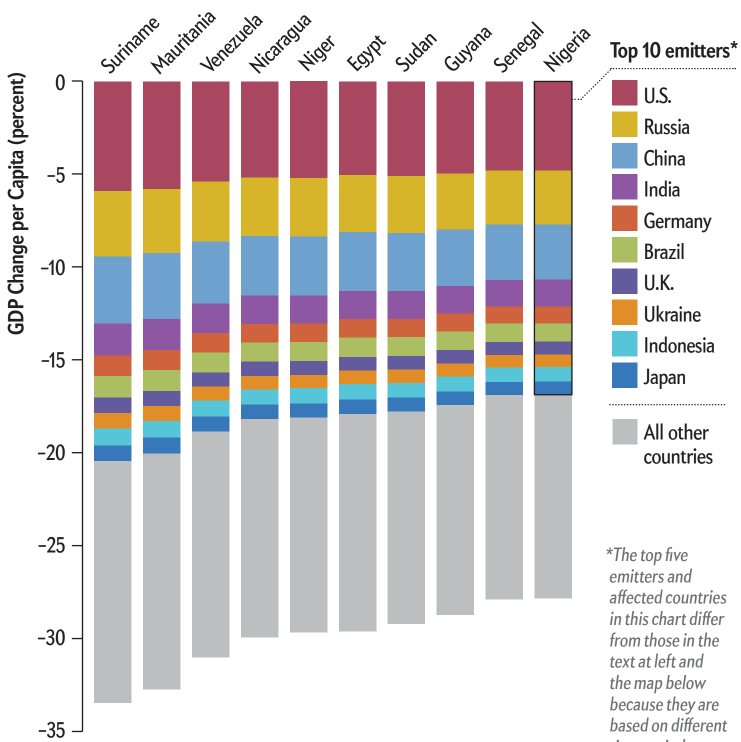
The Cost of Climate Change

How each nation's greenhouse gas emissions have cost others

The top five greenhouse gas–emitting nations—the U.S., China, Russia, Brazil and India—collectively caused $6 trillion in global economic losses between 1990 and 2014, according to a recent study of available data. And those losses haven't been felt equally. Dartmouth College climate scientists Christopher W. Callahan and Justin S. Mankin used climate models to determine how much of the planet's warming could be attributed to each country's emissions and calculated what those emissions have cost every other country. The scientists linked global average temperature rise to the warming in each nation (because some parts of the world are warming faster than others) and then to the associated change in that country's gross domestic product. "A striking feature of the results was the compounding inequalities," Callahan says. Whereas wealthier countries burned more fossil fuels to drive economic growth, low-income countries—which are already less able to adapt to a changing climate—bore the brunt of the losses.

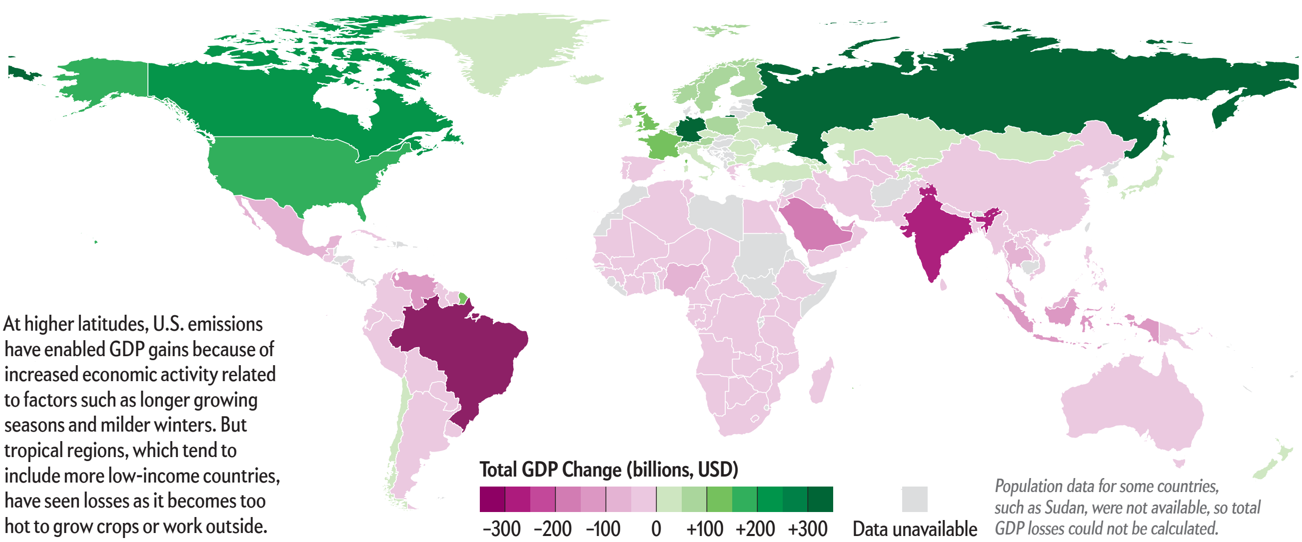
Per Capita Losses from the Big Emitters (1960–2014)

Many of the countries that have contributed the least to the world's climate crisis (such as several of those in the chart below) are disproportionately affected by the impacts of global warming. Scientists showed it is possible to explicitly link emissions from one country to warming and then to economic losses in another. These connections would be necessary for any climate-related lawsuits aimed at holding the biggest emitters accountable, as many seek to do.



*The top five emitters and affected countries in this chart differ from those in the text at left and the map below because they are based on different time periods.

Total Losses and Gains from U.S. Emissions (1990–2014)



At higher latitudes, U.S. emissions have enabled GDP gains because of increased economic activity related to factors such as longer growing seasons and milder winters. But tropical regions, which tend to include more low-income countries, have seen losses as it becomes too hot to grow crops or work outside.

Population data for some countries, such as Sudan, were not available, so total GDP losses could not be calculated.

Source: "National Attribution of Historical Climate Damages," by Christopher W. Callahan and Justin S. Mankin, in *Climatic Change*, Vol. 172; July 12, 2022

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