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The Weight of Empty Space

Redesigning Living Matter

Understanding Witch Hunts

Destination Jupiter

New missions will explore moons with oceans that could harbor life


Enhancing
Human Touch

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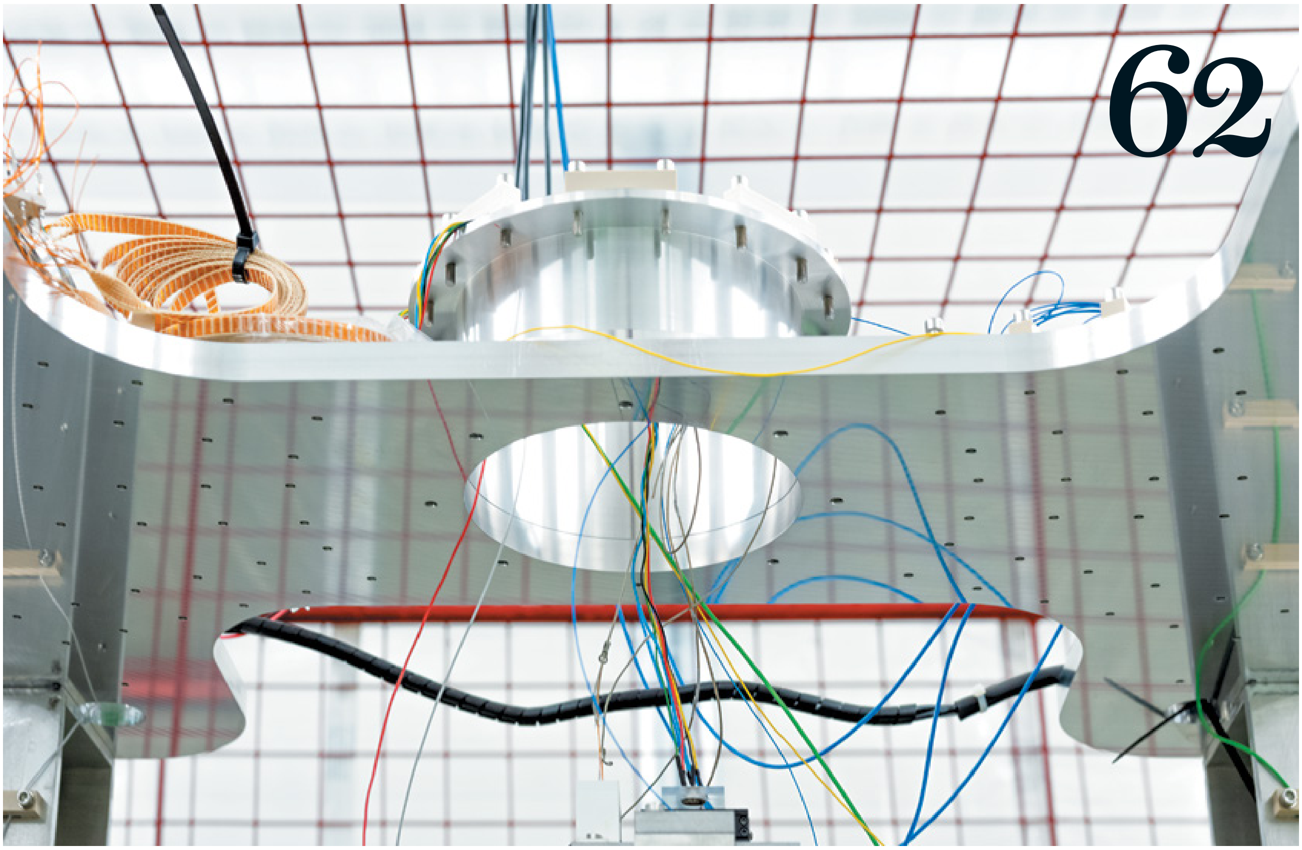

ON THE COVER

Jupiter and its intriguing moons, which may hide buried oceans, will soon get a visit from two new missions. The roving storms on the giant planet are highlighted in this citizen scientist–created image, which exaggerates cloud height, based on data from the JunoCam instrument on the Juno probe. **Photograph by NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill, © CC by 3.0 Unported.**

Photograph by Vincent Fournier

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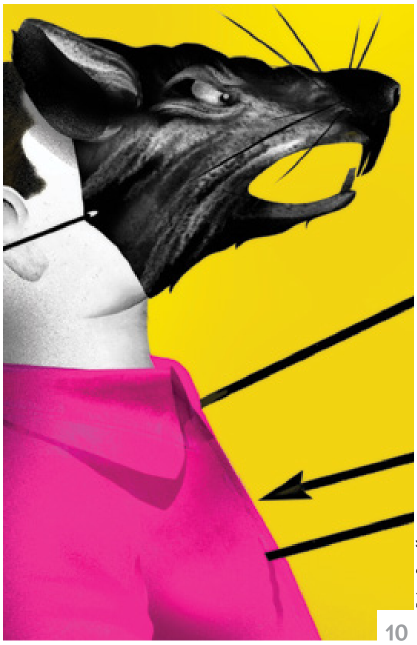
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FROM THE EDITOR

Laura Helmuth is editor in chief of *Scientific American.* Follow her on Twitter @laurahelmuth

Reality vs. Magic

Do you remember learning about New England witch trials for the first time, maybe in an elementary school history class? I remember being horrified and incredulous—they threw you in a river? And if you drowned, that meant you were innocent? Witch trials seemed like an episode from a fairy tale, something that happened unimaginably long ago during a dark, mean and superstitious age. Well, the darkness and meanness and superstitions have persisted. QAnon conspiracists claim that U.S. society is run by Satan-worshipping child abusers—witches, basically. In many countries today, women (and sometimes men or children) are still accused of using magic to cause accidents or other trouble. Their neighbors, justifying their violence by claiming they're punishing a witch, torture and kill them. It all seems so nonsensical and awful, but as historian Silvia Federici and writer Alice Markham-Cantor discuss on page 44, throughout history certain kinds of economic upheaval have increased the risk that witchcraft accusations will erupt and spread.

Let's mentally leave this planet for a moment. What's your favorite planet that isn't Earth? Many of the scientists, journalists and science fans I know are passionately Team Saturn or Team Jupiter. Our cover package makes a great case for Jupiter and its moons being the most awesome places in our solar system. We're about to learn a lot more about them, as journalist Jonathan O'Callaghan tells us on page 30, thanks to two new missions: JUICE and Clipper. They'll evaluate Europa and Ganymede for potential habitability. Starting on page 37, *Scientific American* contributor Rebecca Boyle and graphic artist Juan Velasco depict the interiors of Jupiter's most intriguing moons and where they might have heat and oceans. We end the report with some gorgeous images of Jupiter that were created by citizen scientists (*page 42*).

The "worst theoretical prediction in the history of physics" has to do with the amount of energy in a vacuum. Researchers have two ways of calculating the answer … but the results are wildly divergent. Now an experiment, named Archimedes, aims to get the best data yet to determine the weight of nothing. Theoretical physicist Manon Bischoff, an editor at *Spektrum,* the German-language partner publication of *Scientific American,* takes us deep into a tunnel in Sardinia (*page 62*) to show how the delicate experiment will be run and explain the high stakes.

Transportation is the largest source of greenhouse gases in the U.S. Car emissions have lessened dramatically over the decades, decreasing smog and lead pollution. New technologies for electric vehicles, hybrids and highly fuel-efficient cars can help. But one of the simplest solutions for improving transportation—for our climate, safety and quality of life—is more and better buses. Climate journalist Kendra Pierre-Louis makes a great case for why and how more areas should enhance their bus systems (*page 74*).

An emerging field called synthetic morphology experiments with the structure and function of living things. As author and former *Nature* editor Philip Ball describes on page 54, the goal is to understand how development works naturally while making new types of life-forms that have useful functions. Scientists hope to incorporate living tissue cultures, some of which are genetically engineered, to create "superorgans" or replacement parts—even life-forms we can only imagine. SA

Illustration by Nick Higgins


You're looking at me but are you really *seeing* me?
—Earth
Our world is trying to tell us something.
We have boundless capacity to study our world. But we need to *understand* its connectivity to develop scalable solutions to global challenges and create a healthier trajectory for everything. We're making it happen.
globalfutures.asu.edu
ASU Julie Ann Wrigley Global Futures Laboratory
Arizona State University
Reshaping our relationship with our world

January 2023

"Vitamin D supplementation is likely of little benefit to most people who wish to avoid osteoporosis. But smoking cessation is certainly of great benefit."

DANIEL SPITZER *PIERMONT, N.Y.*

SMOKING AND BONE HEALTH

Claudia Wallis nicely summarizes issues surrounding bone health and calcium metabolism in "A Diet for Better Bones" [The Science of Health]. She mentions the likely deleterious effects of excess alcohol and coffee intake in the article. To this list, I would add cigarettes—in any quantity and at almost any time in life.

A routine part of my practice as a neurosurgeon was the evaluation of patients with osteoporosis and the performance of spinal surgery, including fusion. I rapidly saw that almost all my patients with osteoporosis had smoked, although many of them would initially deny a history of cigarette consumption until specifically asked if they had smoked as a teenager. Even a short history of cigarette use during the prime period for bone growth and ossification—adolescence and early adulthood—was correlated with a significant increase in the risk of osteoporotic fractures during late adulthood.

Similarly the rate of successful spinal surgery—particularly discectomy and fusion—among active smokers was appreciably lower than that for nonsmokers, so I would postpone nonemergent surgery until the patient had been free of cigarette smoke for at least four—and ideally six—weeks. Over the ensuing decades numerous studies have validated my anecdotal observations.

As Wallis notes, vitamin D supplementation is likely of little benefit to most people who wish to avoid osteoporosis. But smoking cessation—or, better yet, never smoking—is certainly of great benefit.

Daniel Spitzer *Piermont, N.Y.*

METABOLIC PATH LESS TRAVELED

I enjoyed "The Human Engine," Herman Pontzer's article on rigorous experiments that determine the age- and lean-mass-adjusted trends of human metabolism. The box "Measuring Metabolism" shows these data in two graphs, and the large degree of scatter about their respective regression curves leads to even more interesting questions.

Each scatter point represents a unique human being who is most likely not "average." Can the scatter explain why certain individuals have more difficulty losing weight or why a particular diet might not work for everyone? How much of it is linked to genetics versus environment? Is it ethical to make health recommendations based on a sample mean when those off the regression curve might be harmed? Furthermore, new cancer therapies tailor treatments to an individual's genetics. Are such considerations being applied to studies of diet and metabolism?

Mark G. Kuzyk *Regents Professor of Physics, Washington State University*

I was surprised that Pontzer's article about human metabolism made no mention of the gut microbiota. Each of us coexists with a complex gut ecosystem that contains more organisms than there are cells in our body. Recent discoveries have made it clear that the gut microbiota influences many aspects of our physiology, from immune function to mental health, and alterations to it induced by widespread use of antibiotics and highly processed foods most likely play a critical role in explaining the epidemic of obesity. The gut microbiota is also the filter through which all of our food is processed, linking it inextricably with human metabolism. It is not just "us" who use the calories we consume, making the "calories in, calories out" formulation Pontzer cites incomplete.

Ira S. Nash *Scarsdale, N.Y.*

PONTZER REPLIES: Understanding the considerable variability we see among individuals in their daily energy expenditure is the next frontier in metabolic research. We now have a good sense for how body size, fat percentage, lifestyle and age affect the calories we burn every day, but as readers Kuzyk and Nash point out, there is a lot of unexplained variation. The degree to which these differences reflect genetics or environment is not well understood at the moment. Our microbiome may well be a critical piece of the puzzle. The evidence on that front is currently sparse, however. Time and more study will tell.

We don't typically find that a "fast" or "slow" metabolism (burning more or less energy than we'd expect for a person's size and age) predicts weight gain or obesity. I do suspect that the metabolic variation we see is telling us something about overall bodily function and health, but those possible connections are yet to be tested.

LOCALITY LOOPHOLE

"The Universe Is Not Locally Real," by Daniel Garisto, reports on how the Bell test has been used to rule out the existence of hidden variables, unseen factors that could explain quantum-mechanical phenomena while preserving local realism. But I'm still puzzled why answering the question of hidden variables has not been declared unsolvable by this technique.

Garisto says "any prior physical connection between components, *no matter how distant in the past* [emphasis mine], has the possibility of interfering with the validity of a Bell test's results." He then describes a "cosmic Bell test" in which researchers used stars that were "sufficiently far apart" so that the light from one wouldn't reach the other for centuries. But assuming that the big bang and cosmic inflation are true, doesn't that mean there is an unavoidable loophole in *every* Bell test because everything was physically connected in the distant past?

Gary Rector *Cave Creek, Ariz.*

GARISTO REPLIES: There have been additional cosmic Bell tests since the one I described in my article, including one that used light from quasars that are separated by billions of light-years. Rector is correct that even these tests go back only so far. As he suggests, this does imply that the big bang remains an unavoidable loophole. It's worth considering what such a loophole-sized theory would presuppose: that hidden variables were encoded at the very beginning of time and space, deterministically setting everything into motion until spacetime's end.

Superdeterminism, as this idea is called, might rescue local realism from quantum mechanics, yet it strips the universe of chance in favor of a conspiratorial approach to experiments. Everything that we can measure suggests that quantum mechanics is correct, that local realism is false. It's worthwhile to be aware of superdeterminism as a possibility. But believing in things because they are impossible to rule out is a poor way to approach science—or, for that matter, anything else.

BEE INTELLIGENT

Bumblebees apparently "play," according to the study reported in "Bee-Ball," by Grace van Deelen [Advances]. This raises a question: Are bees individually intelligent? How about ants? Within a colony these insects are continuously exchanging information in the form of pheromones and other chemicals. A bee or ant colony manifests more intelligence than would be expected by summing the intelligence of the individuals.

Van Snyder *La Crescenta, Calif.*

ERRATUM

In "Primordial Soup," by Clara Moskowitz [March 2023], the box "Quark Soup" should have said that Brookhaven National Laboratory's sPHENIX and STAR detectors each have a powerful magnet at their core, not a powerful superconducting magnet. Only sPHENIX's magnet is superconducting.

LETTERS TO THE EDITOR

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Pandemic Reckoning

After Pearl Harbor, 9/11 and other major calamities, the U.S. has examined itself to see how to prevent the next catastrophe

By the Editors

In better times, the U.S. has, with some humility, owned up to its failures. Commissions have investigated tragedies such as Pearl Harbor and 9/11. Presidential blue-ribbon panels bulwarked the Social Security program in 1983 and overhauled NASA's space shuttle program after the 1986 *Challenger* disaster.

Three years into the COVID pandemic, more than 1.1 million Americans have died of the illness, and millions more are living with long COVID. How did the nation judged most prepared for an epidemic or pandemic in 2019 suffer a death rate so much worse than those of peers such as Canada, Germany or Japan? These are historic failures, and with the Biden administration and Congress coming to a rare agreement that the national health emergency should now end, we need an honest examination of this tragedy and what led to it.

No one is asking in a comprehensive way why states understaffed public health agencies, the federal government left emergency supply shelves empty, test makers were unready for manufacturing, social media and cable news outlets let misinformation run rampant, and everyone ignored past warnings of all these pitfalls. A bill creating a national task force on the COVID pandemic languished in the U.S. Senate. At least eight versions of this task force—modeled on the 9/11 Commission and supported by leading medical and scientific figures in the U.S.—have been proposed and gone nowhere in Congress, according to the Congressional Research Service.

How can we prevent another pandemic if we will not ask what happened? We need answers for the millions and counting who have been devastated by this disease.

We call on Congress and the Biden administration to support a comprehensive COVID Commission to better understand the depths of this disaster and to point the way toward stopping the next global outbreak of a new and deadly transmissible disease.

Short of this, a grieving nation will be left with a patchwork of unconnected investigations of failures, such as the Centers for Disease Control and Prevention's travails in the initial response, and successes, which include the work on mRNA vaccines. There was a Commonwealth Fund report calling for stronger public health agencies. There were too brief advisories from the National Academies of Sciences, Engineering, and Medicine, a body first chartered during the Civil War to advise the U.S. government on that national cataclysm. Congressional committees published Trump administration e-mails in 2021 showing political interference with science. In September 2022 a White House steering committee on "pandemic innovation" released a studiously boring report. It was, at best, a final whimper of the Biden administration's call for increased pandemic funding, which had been stripped from last year's budget deal.

No matter how well intended, none of these efforts examined the totality of the U.S. pandemic response, so none can serve as a focal point for the country to understand what it has gone through. We had hoped that President Joe Biden would call for such a reckoning during his recent State of the Union speech, but the only look back he promised was for fraudsters who stole relief funds. And many House Republicans who have unwaveringly misled their supporters on COVID—needlessly costing lives—have now begun their own unserious hearings aimed at demonizing the federal research agencies behind the very vaccines that saved millions of lives in the pandemic.

We live in a cynical age, and doubts about the prospects of a pandemic commission come all too easily. Yet political scientist Jordan Tama has found high-level commissions to be surprisingly influential in American politics, particularly presidentially appointed ones that aim for structural reforms. Those are the kinds of assessments we need now. We need to know when it is best to use travel bans and masks. We need to know how schools, businesses and hospitals should respond—before the next pandemic hits.

There's plenty of blame to go around in the COVID outbreak, starting with China's silencing of warnings—an authoritarian response that spurred the spread of the COVID-causing virus SARS-CoV-2 worldwide. The scientific community, the medical system and, not least, the press all made countless mistakes in the U.S. response to the pandemic, not just government agencies and elected officials. But none of that matters more than stopping another pandemic from wreaking the same havoc.

Given the division of the national moment, perhaps the most appropriate and authoritative path for a U.S. panel would emulate the truth and reconciliation commissions that have helped countries face deep national traumas—apartheid in South Africa, a murderous dictatorship in Chile and other such ordeals—by seeking restorative justice. The U.S. may need just such an effort after a global pandemic that has ripped the country apart. No nation weathered the pandemic without fault or blemish, but none had a right to expect better results, with less to show for those expectations, than the U.S. We no longer work, live or view the country the way we did before.

A reckoning, whether it comes in the form of a truth and reconciliation commission, a blue-ribbon panel or something akin to the 9/11 Commission, could help us repair the rifts created by our fragmented response and excruciating losses. In his 2023 State of the Union address, Biden described the devastation. "Families grieving. Children orphaned. Empty chairs at the dining room table," he said. "We remember them, and we remain vigilant."

An installation of white flags in 2021 on the National Mall in Washington, D.C., honored the many lives lost to COVID.

BriVisu/Getty Images

But it's a curious kind of remembrance and vigilance that Biden and his colleagues in Congress envision, one that mostly looks ahead for new variants and vaccines rather than asking how we lost so many lives and ruined so many more.

The last truly successful national commission, the 9/11 Commission, conducted a bipartisan investigation into how nearly 3,000 people died on one awful day. Three years into the pandemic more Americans were dying every week from COVID than were lost on 9/11. That amounted to more than 15,000 people gone in January alone, a brutal count added to an ever growing number.

If one death is a tragedy, what are more than one million dead? In the end, are those lost in the pandemic—each grandparent, parent or child—just numbers to the American people? To our elected officials?

The time has come for an answer.

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Bryn Nelson is a science writer and author based in Seattle. He is author of *Flush: The Remarkable Science of an Unlikely Treasure* (Grand Central, 2022). Follow him on Twitter @SeattleBryn

Weaponization of Disgust

Vilifying a person or group of people is linked to increased violence against them

By Bryn Nelson

Before the 2022 midterm elections, David DePape, accused of attacking Representative Nancy Pelosi's husband, Paul, posted a slew of online rants that included references to QAnon, a conspiracy theory that claims that Democratic, Satan-worshipping pedophiles are trying to control the world's politics and media.

Three weeks after the assault on Paul Pelosi, a shooter killed five and wounded 17 at Club Q, an LGBTQ club in Colorado Springs, Colo. The suspect, who has a troubling history of threats and violence, had created a website with racist images and videos that glorified mass shootings.

Neither attack was an isolated incident. With the support of former president Donald Trump, the QAnon conspiracy theory has contributed to a widening spiral of threats and violence, including the deadly January 6, 2021, Capitol insurrection spurred by lies of a "stolen election." Right-wing media personalities and activists have created or amplified conspiracy theories about Nancy Pelosi, Hillary Clinton, Bill Gates, and others.

Dehumanizing and vilifying a person or group of people can provoke what scholars and law-enforcement officials call stochastic terrorism, in which ideologically driven hate speech increases the likelihood that people will attack the targets of vicious claims. Even if we can't predict *how* the violence will boil over, continued demonization means we can be increasingly sure it will.

At its core, stochastic terrorism exploits one of our strongest and most complicated emotions: disgust. In my book *Flush*, I describe how psychologists have come to view disgust as a kind of behavioral immune system that helps us avoid harm. It has a darker side, however: in excess, it can be weaponized against people.

Propagandists have fomented disgust to dehumanize Jewish people as vermin; Black people as subhuman apes; Indigenous people as "savages"; immigrants as "animals" unworthy of protection; and members of the LGBTQ community as sexual deviants and "predators" who prey on children. That horrifying history is now repeating itself as political extremists create dangerous new strains of contempt and hatred.

Fox News's Tucker Carlson has repeatedly hosted right-wing activist Christopher Rufo, who has claimed that drag queens participating in book readings are trying to "sexualize children." A revival of the "groomer" smear against the LGBTQ community has been implicated in an explosion of threats and attacks across the country. In response to one of Rufo's on-air diatribes, Carlson explicitly linked drag queens to pedophiles: "Why would any parent allow their child to be sexualized by an adult man with a fetish for kids?" Rufo then suggested that parents should push back and "arm themselves with the literature" supposedly laying out the child-sexualization agenda. Carlson replied, "Yeah, people should definitely arm themselves."

Some have. Researchers have estimated that transgender people are more than fourfold more likely to be victims of violent crime than their cisgender counterparts. Assailants have threatened to kill drag queens and LGBTQ people, as well as educators, librarians, parents and lawmakers who support them.

Far-right radio ads in swing states repeated falsehoods about transgender people and a QAnon warning that the Biden administration would make it easier for children "to remove breasts and genitals"—an attempt to evoke disgust. Other ads aimed at white audiences claimed minorities are the true aggressors and destroyers of social norms.

What can break this cycle of vilification, threats and violence? Programs to counter extremism, particularly those that emphasize early intervention and deradicalization, have yielded some successes in at-risk communities. An example is a program based in Boston called Online4Good, which teaches students to "promote tolerance and acceptance" through social media campaigns.

We can refuse to buy into "both-sides" false equivalence and the normalization of dangerous rhetoric and extremism. We can do better at enforcing laws against hate speech and incitement to violence. Ultimately we can disengage with media platforms that make money by keeping us disgusted, fearful and forgetful of our own decency—and shared humanity. SA

Illustration by Brian Stauffer

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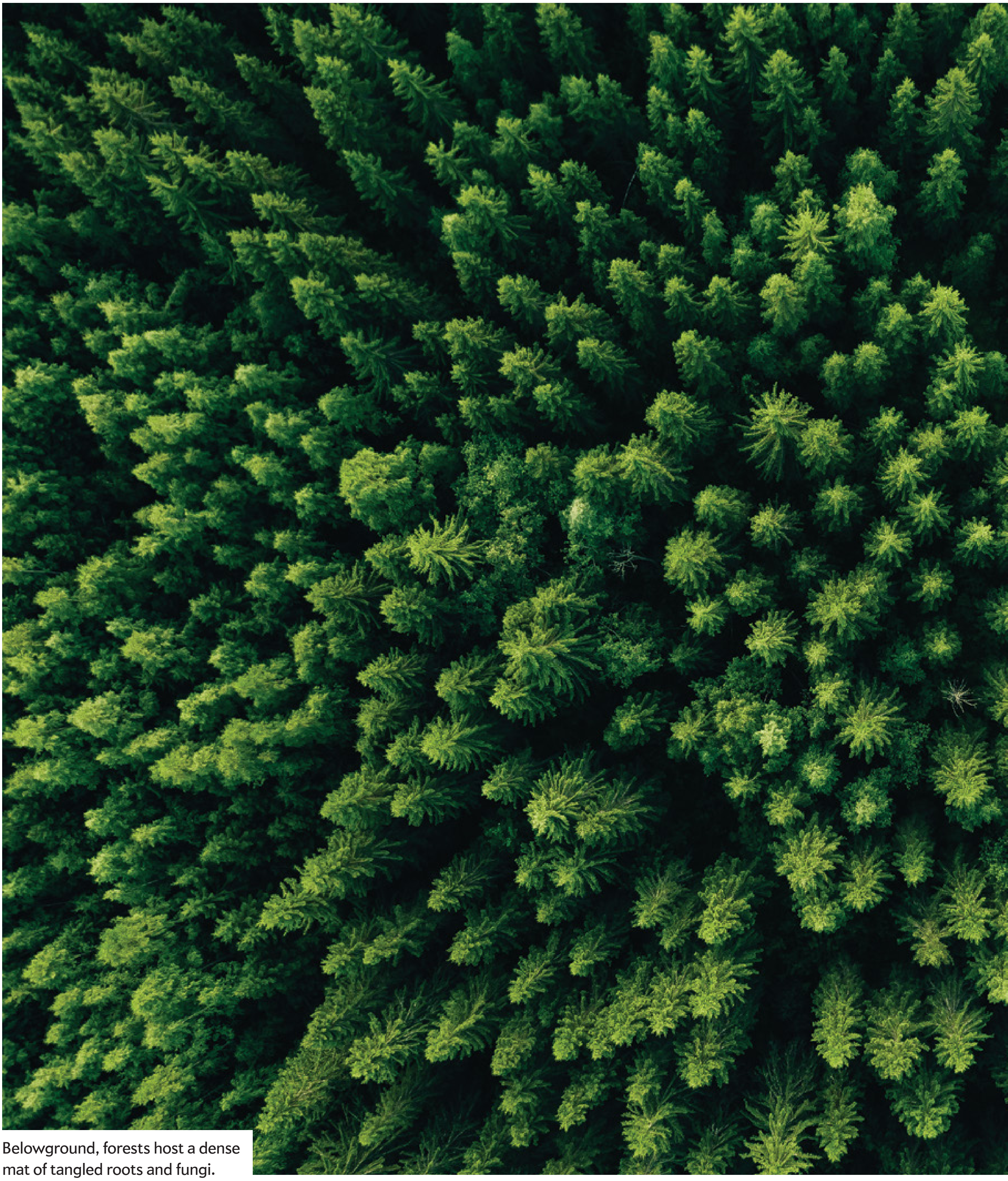
ADVANCES



Belowground, forests host a dense mat of tangled roots and fungi.

INSIDE

wmaster890/Getty Images

ECOLOGY

A Tangled Web

How much do networks of fungi connect trees?

Filaments of fungi intertwine with the tips of tree roots to form underground networks that seem to benefit both organisms: the filaments, called hyphae, break down minerals in the soil that trees can then take into their roots, and the fungi get a steady supply of sugar from the trees.

Research has hinted that these connections—known as mycorrhizal networks—can extend between trees, letting one tree transfer resources belowground to another. Some scientists even argue that trees are cooperating, with older trees passing resources to seedlings and nurturing them as a parent might.

This idea of forests as cooperative, caring places has caught on in both scientific literature and popular culture, notably in the 2021 book *Finding the Mother Tree: Discovering the Wisdom of the Forest,* by University of British Columbia forest ecologist Suzanne Simard. There is even a punny name for the phenomenon: the "wood-wide web."

A new analysis published in *Nature Ecology & Evolution,* however, argues that the evidence for mycorrhizal networks facilitating tree cooperation is not as strong as the popular story would suggest. It's not that relationships between trees and fungi don't exist, says co-author Justine Karst, an ecologist at the University of Alberta. Rather, in many cases, suggestive lines of evidence or studies with many caveats have been taken as more definitive than they really are. "We don't want to kill anyone's joy or curiosity or wonder about the forest, but we want to tamp down on some of the misinformation," Karst says.

Mycorrhizal networks are delicate: dig up a root, and you've destroyed the very web of fungi and wood you wanted to study. To begin to figure out if a particular fungus really connects any two forest trees, scientists can sequence the fungus's genes; this is a lot of work, Karst says. She and her co-authors could find only five such studies across two forest types, comprising only two tree species and three fungi varieties.

And fungal networks' ephemeral nature makes these studies even more complex. Fungi can grow as individuals after their underground connections are split, says study co-author Melanie Jones, a plant biologist at the University of British Columbia—so even genetic samples can't reveal whether the bits of fungi collected at two different trees are still actually connected.

These limitations raise questions about how widespread mycorrhizal networks are and how long they last. Researchers have verified that substances provided to one tree can be taken up by a neighboring tree in the forest. But it's not clear that fungi are necessarily responsible for this transfer, Jones says. Resources can also move directly from root to root and through pores in the soil, and it's difficult to experimentally separate those pathways without disrupting tree growth.

The strongest evidence for trees sending resources via fungal pathways in a forest comes from a 2008 study in which mesh allowed fungi, but not roots, to connect ponderosa pine seedlings to older pines, Karst and Jones say. Dyes applied to cuts in older pines showed up in seedlings, suggesting water transfer via fungal hyphae. But the study authors say evidence is shaky that such water transfer actually improves seedling survival. "In the really well-controlled experiments, less than 20 percent show that the seedlings performed better," Jones says. In the remaining 80 percent, she adds, hyphae-connected seedlings performed either equivalently or worse than the ones cut off from the fungal network.

Meanwhile another idea—that trees share underground warnings about herbivorous insects or other dangers—is predicated on a single greenhouse study, the researchers say, in which researchers connected a Douglas fir and a ponderosa pine only by fungal networks. When scientists exposed the fir to insects, the pine also started pumping out defense chemicals. The effect disappeared, however, when the firs and pines were connected by both roots and fungi, as happens in the wild. "The main message is that this hasn't been tested in a forest," Karst says. "When you see those pictures of ancient forests, big trees … passing signals to each other—it just hasn't been tested."

The main argument for cooperative for-

ENVIRONMENT

Antarctic Shield

Phytoplankton in the Southern Ocean help to whiten Earth's clouds

After sunlight completes its eight-minute journey to Earth, white surfaces such as clouds send much of it bouncing right back into space. The whiter and brighter the cloud, the better it is at reflecting sunlight—and at keeping Earth cool. Now, a study published in *Atmospheric Chemistry and Physics* examines a surprising part of this process: how tiny aquatic creatures known as phytoplankton play a big role in whitening Earth's clouds.

Scientists used satellites to monitor the skies above a large swath of the Southern Ocean for five years. They found that clouds forming south of 60 degrees latitude—that is, closer to Antarctica—tended to be significantly whiter than clouds farther north.

The reason? Minuscule ocean phyto-

Yva Momatiuk and John Eastcott/Minden Pictures

Clouds over South Georgia Island in the Southern Ocean ests is that trees in a healthy forest survive better than trees in a sickly one. But such instances of natural selection as a group are rare in the wild, says Kathryn Flinn, a plant community ecologist at Baldwin Wallace University in Ohio, who was not involved in the new analysis. And in forests, individual selection favors competition, with trees vying for resources in a way that would prevent group benefits. "I find this whole controversy really interesting because it's an example of people wanting to project their own values onto nature and of them wanting to see in nature a model for human behavior," Flinn says.

Simard, whose forest research has provided much of the basis for the assertions that trees cooperate, responded to questions with a statement that she stands by her research. "Forests provide crucial support to life on our planet. Reducing ecosystems to their individual parts hinders us from understanding and appreciating the emergent relationships and behaviors that make these complex ecological systems thrive," she says. "For decades a compartmentalized approach has hindered us from better understanding why forests help to regulate global climate and harbor such rich biodiversity. Applying reductionist science to complex systems accelerates the exploitation and degradation of forests worldwide."

The new study's authors note that most of the experiments available are narrow in focus, and they have already been used to make big claims about mycorrhizal networks. The researchers chose to focus on the subset of studies conducted in real forests, they add, because those are most relevant to the real world.

Karst says that she and her colleagues hope to push research into additional forest types and encourage investigation of the most promising areas, such as water transfer between trees. For her part, Karst thinks mycorrhizal networks may be involved in at least some tree-to-tree networking, and better-designed experiments could get at that truth. "I want to have another go at it," she says.

—Stephanie Pappas

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plankton, says University of Utah atmospheric scientist Gerald Mace, the study's lead author. The Antarctic is "a very highly productive region" where tiny creatures such as phytoplankton proliferate more than they do in seas farther north, he says. As part of their metabolism, many of these sunlight-consuming organisms release a compound called dimethyl sulfide, which rises and reacts with gases in the atmosphere to form small aerosol particles—and, eventually, clouds.

Water vapor typically must first bind to a "seed" particle to condense into cloud droplets, says Max Planck Institute for Chemistry biogeochemist Meinrat Andreae, who was among the first to study phytoplankton's cloud-seeding abilities but was not involved in the new study. South of 60 degrees latitude, abundant phytoplankton generate plenty of dimethyl sulfide seeds—so clouds that form there are full of tiny water droplets.

In more northern areas, cloud-forming seeds are less common—"mostly just salt particles that get swept up from ocean spray," says University of Utah atmospheric scientist and study co-author Sally Benson. The resulting clouds have fewer and bigger droplets, providing less surface area to reflect back sunlight than southern clouds' many small droplets, the researchers say.

The study also found that phytoplankton populations, measured by satellite views of the green compound chlorophyll in the water, peak every summer—soon followed by peaks in cloud reflectiveness. Mace notes that phytoplankton's role in this process is a global phenomenon, but the effect is clearest in the Southern Ocean with its plentiful plankton population and low level of human influence.

Although phytoplankton's involvement in cloud whitening has been known for some time, Andreae says that existing climate models still lack sufficient data to fully account for its effects. He adds that a study of this scale—monitoring a large ocean region over five years—helps to illuminate new patterns, such as the strong link between cloud whiteness and latitude. "With a study of this size," he says, "we can definitely plug better information into our models."

—Daniel Leonard

ANIMAL BEHAVIOR

Far-Ranging Fox Trot

Arctic foxes' transcontinental trips may spread diseases

Under an around-the-clock summer sun, a young Arctic fox set out in July 2019 from Bylot Island in Nunavut, Canada. He wandered over the tundra for 299 days, probably alone, trotting an astonishing 6,400 kilometers before reaching a new home. A tracking collar confirmed the record-breaking journey.

"We knew Arctic foxes could go far," says University of Quebec ecologist Dominique Berteaux, who has led an Arctic fox–tracking project for 20 years. "But we didn't know whether this was a rare behavior or just how far they'd go." Indigenous communities have described the small foxes traversing entire continents, Berteaux adds, and widely separated fox populations have similar genetics. There are various likely reasons for such trips: parents often chase juvenile foxes away from their birth territory to keep competition low, for example, and mature foxes can be pushed out by stronger individuals.

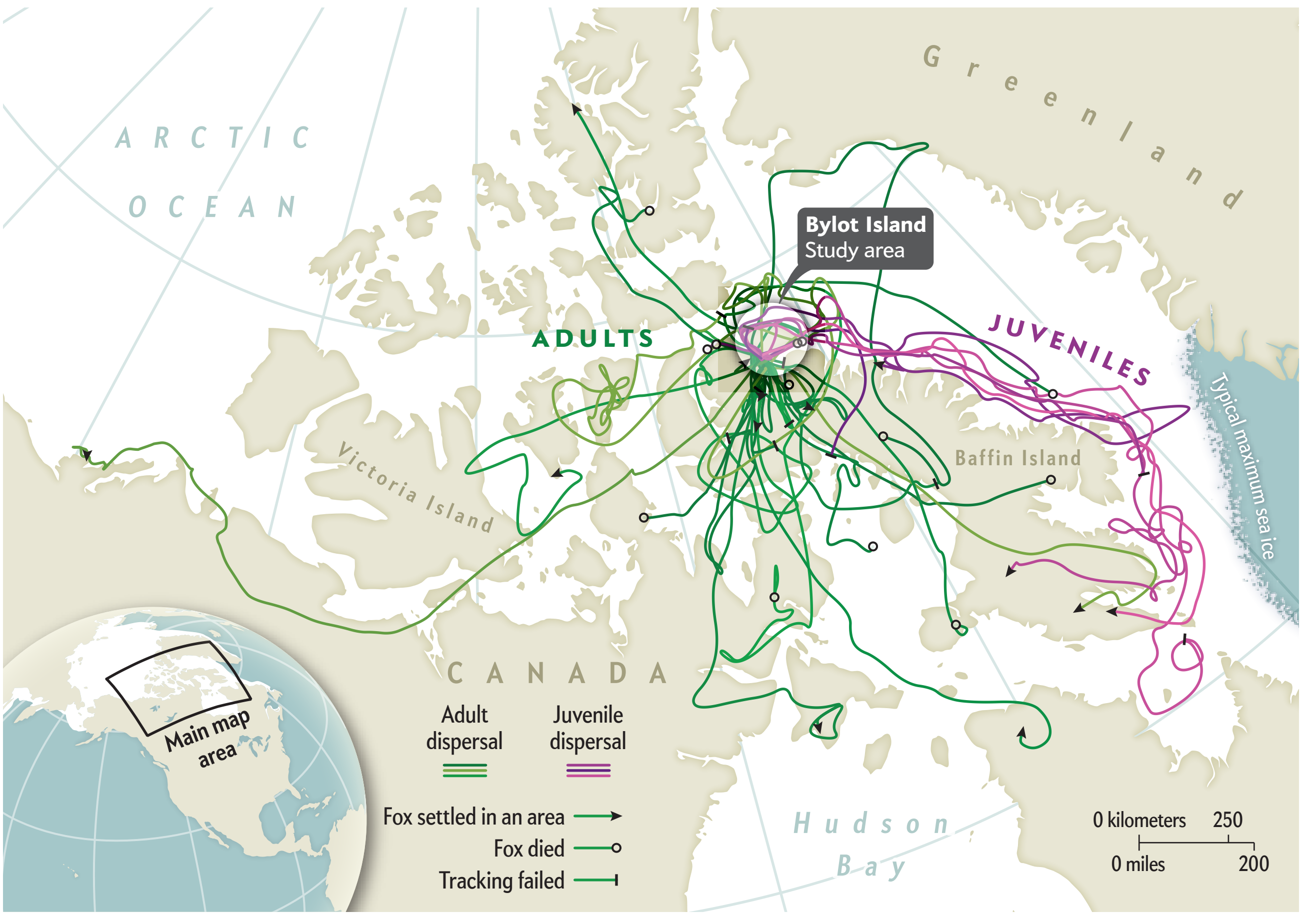
For a recent study in *Royal Society Open Science*, Berteaux's team collared and tracked 170 foxes from 2007 to 2021. Among them, 37 attempted long-distance relocation journeys. Berteaux had expected the vast majority of migration attempts to be unsuccessful. Predators, starvation and other dangers make the treks risky, he says: "They try to find another spot, but it is difficult." Of the 37 long-haulers, however, 13 successfully settled in new territory while their tracking collars were working.

"These small animals are so impressive," says Eva Fuglei, a biologist at the Norwegian Polar Institute, who was not involved in the study. "With a satellite tag, we can follow the footsteps of the Arctic fox. It's fascinating to see how fast they walk."

A surprising 20 percent of the epic trekkers were adults, upending assumptions that only younger foxes could handle such travel. This insight is especially relevant to scientists studying "the spreading of zoonoses—diseases—which can be very dangerous to humans," Fuglei says.

Previously, researchers had assumed adult Arctic foxes were unlikely disease vectors because of less movement. The new study shows, however, that a significant number of hardy older foxes can and do cross continents, potentially bringing parasites and illnesses with them.

—Rebecca Dzombak



The map shows the journeys of 27 adult foxes and 10 juveniles that dispersed over long distances. An additional two young foxes settled less than 80 kilometers away from their birthplace, and four others died shortly after departing. Eva Fuglei notes that tracking collars let researchers see "through the polar night" and document the foxes' winter behavior, which is much less well understood than spring behavior. They also revealed that juvenile foxes relied heavily on sea ice for their travels, suggesting that shrinking ice extent will affect future dispersals.

Source: "Long-Term Satellite Tracking Reveals Patterns of Long-Distance Dispersal in Juvenile and Adult Arctic Foxes (*Vulpes lagopus*)," by Richard Gravel et al., in *Royal Society Open Science*; February 1, 2023 (*fox dispersal data*); National Snow & Ice Data Center (*sea ice data*)

Map by Daniel P. Huffman

POLLUTION

Microplastics Alert

A new trick helps satellites track worsening ocean pollution

Despite their name, microplastics are a gigantic player in pollution worldwide. These fibers, beads and fragments (defined as being less than five millimeters in size) have infiltrated nearly every environment, especially oceans. To track the problem, researchers are now homing in on these seaborne flecks from more than 300 miles away—in space.

Recent research in *Scientific Reports* details how microplastics appear to flow alongside floating patches of oily and soapy substances called surfactants, which create distinct footprints in ocean currents. Those footprints are detectable by NASA's Cyclone Global Navigation Satellite System (CYGNSS), a network of eight hurricane-monitoring satellites, and tracking them could help map microplastics' spread, aiding cleanup and regulation efforts.

"In general, there are insufficient data about microplastics concentration in the ocean," says University of Michigan marine engineer and study coauthor Yulin Pan. Computer models and samples from trawling nets are helpful but incomplete, Pan adds: "That is one of the reasons that we really want a remote sensing technique, to have a general understanding."

The CYGNSS satellite radar measures the ocean surface's roughness, caused by wind-generated waves. In 2021 CYGNSS researchers noticed the radar picking up peculiar areas of smoothness with fewer and smaller waves. The scientists realized these anomalies lined up with the notorious Great Pacific Garbage Patch—and seemed to correlate with levels of microplastics in the water. These initial findings were later used to track microplastics' flow in other hotspots.

But researchers still didn't know the mechanism behind the smoothness or whether it might be linked to factors aside from microplastics such as marine life, other debris, or chemical interactions. Isolating microplastics' influence is "hard if you don't have good training data, where you have microplastics in one part of the ocean and then you can remove them all and test it again," says University of Washington mechanical engineer Michelle DiBenedetto, who studies microplastics fluid dynamics and was not involved in the new research.


Trash in the Pacific Ocean

Wend Images/Alamy Stock Photo

For their study, Pan and his CYGNSS colleagues did the next-best thing: they used a 750,000-gallon indoor wave tank to simulate real-world currents. They found that microplastics alone, at their reported ocean concentration, did not generate matching patches of smoothness. Instead the smoothing came when the researchers added surfactants. These chemicals—which influence wave activity by decreasing the water's surface tension—often accompany microplastics as a by-product of plastic production and breakdown and are carried on the same ocean currents. Because the satellites easily spot surfactants' smoothing effect, the substances can act as a tracer for microplastics' movements, the researchers say.

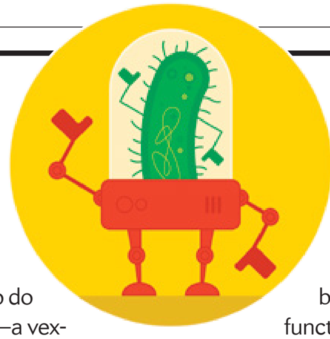
DiBenedetto says tracing surfactants is a tactic "worth pursuing," but more information is needed on their relationship with microplastics in a field setting. This summer the CYGNSS team is coordinating with National Oceanic and Atmospheric Administration research vessels to compare satellite data with water samples from the Great Pacific Garbage Patch. This comparison should further solidify the correlation between surfactants and microplastics, Pan says.

Microplastics "can persist for a really long time," DiBenedetto says. "If we want to invest in solutions, we want to know how plastic naturally moves around so that we can most optimize our resources and go after the places we can make the biggest difference." —*Lauren J. Young*

SYNTHETIC BIOLOGY

Cyborg Cells

Bacteria with synthetic skeletons could be used as tiny robots



Scientists have implanted an artificial hydrogel scaffold into bacteria to create semisynthetic “cyborg cells” that could one day function as tiny robots in medicine, environmental cleanups and industrial production, according to a recent study in *Advanced Science*.

In addition to making the cells hardier, this scaffolding eliminates their ability to reproduce so they can be controlled better than genetically modified live bacteria. The cyborg cells are also easier to create than fully artificial cells of similar complexity.

“We never thought this would work,” says synthetic biologist and study co-author Cheemeng Tan of the University of California, Davis. “When you introduce a gel matrix into cells, most of the time you would think you would kill them.” But his team decided to try.

To build a biological robot, researchers often hack a living microbe’s genetic code to adapt the organism to an intended purpose. But billions of years of evolution have taught microbes not to do things that endanger them—a vexing situation for synthetic biologists who want cells to produce valuable but toxic chemicals or to do other hazardous jobs.

“They’re not stupid; they’re not going to do something that doesn’t make them either divide better or grow better,” says University of Minnesota synthetic biologist Kate Adamala, who wasn’t involved in the new study. “That’s kind of their business model.”

Because fully artificial cells don’t reproduce or have survival instincts, they’re easier to control than live cells. But it’s often hard to make them sophisticated enough for complicated jobs. “In terms of complexity, they’re just no match for natural cells,” Tan says.

To make cyborg cells, the researchers infused live *Escherichia coli* with a hydrogel, which Tan likens to a dense mass of wet molecular noodles. This fortification made the cells sturdier, letting them survive toxic stressors that would kill ordinary *E. coli*. Such cells fall somewhere between artificial and natural: they can’t divide but otherwise have normal function and metabolism. The team also showed that cyborg cells can be programmed with genetic “circuits” (sets of genes that let cells do simple computations) and equipped with genes that help them invade tumor cells.

Scientists have incorporated hydrogels into fully artificial cells before. But hydrogel components are “superhard to control” within a living cell, Adamala notes. Tan says the group stumbled onto the right hydrogel basically by accident—and spent months fine-tuning the recipe so bacteria could survive it.

Tan and Adamala agree that turning other cell types into cyborgs could be useful; yeast, for instance, is a fungus that can make proteins bacteria can’t. For now Tan’s team is working on programming cyborg bacteria to deliver vaccines and act as tiny terminators for cancer cells. —*Elise Cutts*

ASTROBIOLOGY

Creatures from the Brown Lagoon

Microbes from a dry Spanish lake may hold lessons about Mars

As central Spain’s Tirez Lagoon dried up over 20 years, becoming entirely desiccated by 2015, its barren landscape began to evoke arid Martian plains. That resemblance, it turns out, could be useful: researchers are watching the newly dead lagoon’s microbial residents to learn what could have happened to hypothetical life on Mars when its salty lakes dried up billions of years ago.

“The take-home message is that if life existed on Mars when the planet had liquid water on the surface, the global desiccation of Mars would have not necessarily implied that life disappeared for good,” says Alberto G. Fairén, an astrobiologist at the Spanish Astrobiology Center in Madrid.

Analyzing microbes in Tirez soil samples from 2002 and 2021 for a study in *Scientific Reports*, Fairén and his colleagues found that single-celled organisms called prokaryotes had adapted to thrive in extremely dry sediments. These results suggest microbes that developed in wetter conditions could have endured after the Red Planet dried out. The researchers also measured traces of fatty acids called lipids, which form in cell membranes, in the 2021 samples—and the team confirmed that these long-lasting molecules would be a good target in searching for signs of previous life on other planets.

Astrobiologists often study extreme Earth environments that could resemble those of other planets. The Tirez team, however, says its new study presents the first long-term “time analog” of environmental changes on another world. Researchers had been interested in the lagoon’s high salt concentration as a proxy for Jupiter’s moon Europa, which some have hypothesized may hold life. But in 2020 Fairén got the idea to use the decades of lagoon data to learn about early lakes on Mars instead.

As this type of study helps researchers understand faraway worlds, it can also be useful closer to home. Time analogs raise “an interesting idea—that not only should we explore more for understanding Mars but also our own planet,” says Nathalie Cabrol, chief scientist at the SETI Institute, which focuses on the search for extraterrestrial intelligence. Cabrol, who was not involved in the study, says there is a “dire need” for research on how fast Earth’s biospheres are morphing because of climate change.

Fairén’s team is currently planning two new time-analog studies. First, if Spain’s long dry spell ends, Fairén hopes to measure how Tirez’s microbes respond to water reentering the lagoon. Second, he wants to study ecological change in polar environments where ice is melting at increasing rates to compare it with the period when Mars lost its surface ice. He’s convinced such research will inspire other scientists to take advantage of changing environments for their own studies—learning more about life both on Earth and beyond.

—*Allison Gasparini*

Illustrations by Thomas Fuchs

A dolphin and a fisher in Laguna, Brazil

Angelo Gandolfi/Minden Pictures

ANIMAL-HUMAN COOPERATION

Swim Team

A famed dolphin-human partnership brings mutual benefits

People in Laguna proudly refer to their southern Brazilian city as the "national capital of fish-herding dolphins." For at least 140 years artisanal fishers and bottlenose dolphins have worked together in careful synchrony to catch mullet in a local lagoon. The spectacle of nets flying through the air while dolphins dive into the murky water has become a popular attraction for tourists, and it is recognized by local authorities as an intangible cultural heritage.

In 1998 scientists confirmed that this renowned example of human-wildlife cooperation aids at least one of the parties: the fishers, who enjoy larger catches when they join forces with dolphins. Most believed that the dolphins were reaping rewards, too, but this hypothesis was more difficult to test.

Now researchers have finally documented that the benefits are indeed mutual. An exhaustive new study published in the *Proceedings of the National Academy of Sciences USA* shows that dolphins that team up with fishers gain more food and have an edge in survival compared with those hunting without human partners.

Laguna's resident population of up to 60 dolphins uses echolocation to find schools of mullet that humans are unable to detect in the opaque water. Then the cetaceans herd a school toward the fishers, who are typically standing in the shallows just offshore. The dolphins give a cue, such as a sudden deep dive, to let the fishers know when to cast their nets; the net casting in turn breaks up the school of speedy fish, making it easier for dolphins to capture individual mullet.

"Each [species] brings a new skill to the table that increases their mutual success," says Mauricio Cantor, the study's lead author and a behavioral ecologist at Oregon State University. The research indicates, however, that these celebrated interspecies hunts are in danger of vanishing. "Our data suggest this interaction is becoming rarer over time," Cantor says. "If things continue the way they are, these interactions might disappear in the next 50 to 60 years."

Laguna's cooperative fishers and dolphins are one of the few remaining examples of a millennia-old tradition across the world. Fossil evidence from Europe indicates that humans and wolves might have collaborated to hunt prey as early as 32,000 years ago. In the first century C.E. Pliny the Elder mentioned fishers working with dolphins in what is now southern France. Since then, seemingly cooperative interactions with people have been recorded in at least 16 species—mostly cetaceans but also some birds—in countries such as Australia, Myanmar, Mauritania and Japan.

Many such collaborations have ended, however. And those left are almost all in decline because of pollution, overfishing and habitat loss, combined with the general disconnection of humans from the natural environment. "Today most interactions we have with wildlife tend to be antagonistic and not mutually beneficial," Cantor says. "So it's really important to understand how these

Continued on page 20

Continued from page 19
things happen and what we can do to safeguard this unique biological phenomenon."

To analyze Laguna's human-dolphin cooperation, Cantor and his colleagues collected data using drones, underwater microphones, sonar cameras, GPS and interviews with fishers. The study's senior author, Fábio Daura-Jorge of the Federal University of Santa Catarina in Brazil, also provided 15 years' worth of survey responses from fishers, as well as photographs and dolphin behavior records for both individual animals and groups.

After pulling it all together, the researchers found that fishers were 17 times more likely to catch mullet when they worked with dolphins than they were on their own, and dolphins had more success in these partnerships as well (the researchers are still working to quantify the dolphins' gains). Dolphins that partnered with fishers also experienced a 13 percent boost in survival, most likely because they spent most of their time in the lagoon. In areas nearby, some fishers use illegal drift nets that drown dolphins as bycatch.

These findings support "the long-standing hypothesis that these dolphins experience a higher prey capture rate when interacting with fishers," says University of Cape Town behaviorial ecologist Jessica van der Wal, who was not involved in the research.

The team also built a model to predict how fisher-dolphin interactions might change over time. Fishers have anecdotally reported a decline in joint hunting practices over the past 15 years, and the model suggests that this trend will continue, putting the practice in danger of extinction. The main drivers for that decline, the authors found, are decreasing mullet populations caused by overfishing and climate change, along with livelihood changes in the artisanal fishing community.

The scientists propose some solutions to help prevent this loss: Fishers, for example, could be incentivized to keep working with dolphins if buyers of their catch were willing to pay a premium for their fish. This way, Cantor says, "even if catch declines over time, there will be a higher reward for fishers in monetary terms."

Protecting dolphins from becoming bycatch would also help. The government could invest in more policing to remove illegal nets and apprehend violators. And raising awareness is key. "Getting people excited about these rare phenomena is a way to add more value to these kinds of cultural practices that seem to be fading away," Cantor says. "Preserving cultural diversity has been shown to promote the preservation of biological diversity as well."

The "exemplary" new study is "of huge importance" for showing both how this cooperation is achieved and how it can be conserved, says University of Bristol behavioral biologist Stephanie King, who was not involved in the research. "Humans are renowned for the ways they cooperate," she says, "but what is even more remarkable is two distantly related species with very different evolutionary histories acting cooperatively to achieve a common goal."

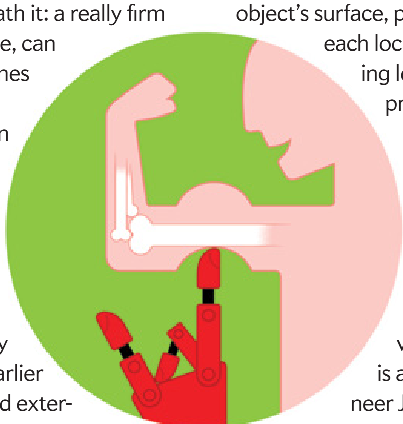
—*Rachel Nuwer*

TECH

Bionic Finger

A fingerlike device pokes objects to sense their internal structures

Human fingers don't just sense what a surface feels like. They also tell us a lot about what's underneath it: a really firm handshake, for example, can reveal where some bones are, and, with enough prodding, one can even locate tendons.



Inspired by this capability, scientists have developed a fingerlike device that maps an object's internal structures in 3-D by touching its surface. Earlier tactile sensors detected external shape, stiffness and texture but not subsurface details. For a study in *Cell Reports Physical Science*, the researchers tested their device by scanning simulated human tissue and electronic circuitry.

"This bionic finger has exciting application prospects in material characterization and biomedical engineering," says study coauthor Zhiming Chen, an engineer at China's Wuyi University. "The technology could also be incorporated into robots and prosthetics, which is our next research topic."

The new "finger" contains a carbon fiber tactile sensor, which returns a stronger signal when compressed against stiffer objects. The device moves across an object's surface, poking several times at each location to feel for increasing levels of pressure. This process can reveal subsurface details, such as hard layers inside softer materials. "When pressed by this bionic finger, hard objects retain their shape, whereas soft objects deform when sufficient pressure is applied," says Wuyi engineer Jian Yi Luo, the study's senior author. "This information is transmitted to a computer, along with the recorded position, and displayed in real time as a 3-D image."

Other imaging methods, including x-ray, PET, MRI and ultrasound, have their own pros and cons. X-rays carry health risks, and other options lack portability or speed. Many are expensive. The new device is unlikely to be significantly cheaper than ultrasound, but it may provide better resolution. "It offers another way of doing things, which has its own advantages in specific contexts," says University College London engineer Sriram Subramanian, who was not involved in the work. "I don't think it's easy to do ultrasound imaging of printed electronic circuits."

In simulated human tissue, the device pinpointed bones and a blood vessel. For a flexible electronic circuit encapsulated in soft material, it detected a circuit break and an incorrectly drilled hole. "When we make those [devices], we always worry that if something is broken, the only way you can know is to take it apart," Subramanian says.

The device will struggle to map objects whose outer surface is too hard, and it may miss details underneath hard layers. The researchers plan to extend their invention into more dimensions, however, perhaps probing from other directions as well. "This system might be expanded to multiple fingers, just like our hands, to realize 'omnidirectional' detection," Chen says. "This would enable it to get more complete information."

—*Simon Makin*

CONSERVATION

Bird Barrier

Deterrent film halts bird strikes only on windows' outdoor sides

Hundreds of millions of birds die every year from smashing into windows, one of the biggest sources of human-caused bird deaths—far greater than wind turbines and airplane strikes combined. In a bid to help birds see the panes before it's too late, people may stick decals or tinted films on their windows—often on the indoor side. But a recent study in *PeerJ Life & Environment* shows that such films work only on a window's outside surface.

"Putting these window films on the inside really is not giving you the benefit that you would want for protecting the birds," says John P. Swaddle, a biologist at the College of William and Mary and lead author of the new study.

To test the films' effectiveness, Swaddle and his colleagues applied one of two commercially available films to either interior or exterior window surfaces. One film reflected shorter light wavelengths that humans cannot see, and the other reflected longer wavelengths (many birds can see both). The researchers also mounted superfine nets in front of the windows to keep birds from actually hitting the glass. Both films helped to prevent bird strikes by more than 35 percent when put on the outside surface, the study found—but films on the inside had no benefit at all.

"It's some groundbreaking work about the nuances of what can and can't work in terms of preventing window strikes from birds," says George Mason University biologist David Luther, who studies the evolution of birds in cities and was not involved in the study.

People usually find it much easier to put films or decals on the indoor side of a window, says Natalia Ocampo-Peñuela, a conservation ecologist at the University of California, Santa Cruz, who was also not involved in the study. For taller buildings, to apply something to the outside, "you need scaffolding … you need to clean the windows extra well for them to apply correctly, and they don't last as long."

Swaddle hypothesizes that films placed on the inside don't effectively interrupt the reflection and scatter of exterior light. This might also be the case with decals, although those were not tested in this study, he says. In future studies, the researchers will continue exploring how birds see and experience the world, which could further help bird lovers, architects and manufacturers prevent avian deaths. —*Susan Cosier*

Alan Murphy/BIA/Minden Pictures

NEWS AROUND THE WORLD

Quick Hits

By Allison Parshall

AUSTRALIA

Male quolls, endangered Australian marsupials, die after one mating season—and new research using radio trackers shows why. Scientists found the quolls sacrifice sleep and travel long distances to find a mate, likely making them weak and reckless. One walked 6.5 miles in one night—equivalent to 24 miles for a human.

FRANCE

Cryptographers decoded 57 hand-encrypted letters from Mary, Queen of Scots, who was arrested and later beheaded as a rival to Queen Elizabeth I. The 16th-century letters were mostly addressed to the French ambassador to England, revealing Mary's extensive political efforts while imprisoned.

INDIA

A cave wall discovery originally identified as a 550-million-year-old fossilized *Dickinsonia* sea creature is actually residue from a present-day beehive, researchers say. The finding revives debate about nearby formations' geological history.

KENYA

A 2.9-million-year-old tool set used to butcher hippos is the earliest example of simple, flaked stone items from what is called the Oldowan tool kit. The artifacts may not have human origins, though—they were excavated alongside teeth from an extinct hominin branch, *Paranthropus*.

RAPA NUI (EASTER ISLAND)

A previously unknown *moai*, one of the famous volcanic rock statues, was discovered in a lake bed that is drying up as a result of climate change—and archaeologists say there may be more underneath the reeds.

U.K.

Ynys Enlli, a tiny Welsh island shielded from mainland light pollution by a mountain, has become Europe's first certified "dark sky sanctuary." It has two year-round human inhabitants and a nesting site for nocturnal seabirds that need dark skies to fly home.

For more details, visit www.ScientificAmerican.com/may2023/advances

BIOLOGY

Chloroplast Choreography

Inside plant cells, chloroplasts transition to a glass state to soak up light

Plants are active life-forms down to their very cells. Within seconds of light exposure, some plants' chloroplasts—the cellular organs that convert light to energy—will begin to scramble around and then congeal again in a flat layer when the light dims.

"They make this mesmerizing, nice building behavior," says Nico Schramma, a physicist at the University of Amsterdam. In a new study, he and his colleagues found that chloroplasts, when they cram together against the cell wall in low lighting, actually become a type of "glass." The study results help to explain how chloroplasts can flip-flop between a rigid solid and a flowing liquid to best soak up the sun.

Glass, to a physicist, is a broad category of solid matter. Hard candy can be glass. Same with plastic—and even spreadable mayonnaise, by some measures. Unlike crystalline structures such as ice, which are solid because of their particles' orderliness, the disordered particles of a liquid transition to glass when they get jammed together so tightly that they can barely move.

Schramma's team found that chloroplasts can undergo a similar process. The physicists tracked chloroplasts in the aquatic plant *Elodea densa* in different light conditions to build a model of their movement, and they soon recognized hallmarks of a glassy system in the data. The results, published recently in the *Proceedings of the National Academy of Sciences USA*, show that instead of individual chloroplasts slowing in low light, they were clustering and trapping one another.

The findings are "very compelling evidence of a glass transition," says Lisa Manning, a biological physicist at Syracuse University, who was not involved in the work. Recognizing this process will let physicists study chloroplasts' complex dynamics as a familiar type of system, the researchers say.

The results also reveal hidden parallels to other glassy living systems. These glass transitions serve an important purpose: flexibility. Developing embryos, for example, move between fluid and rigid. And hard tumors spread across the body by behaving like liquids.

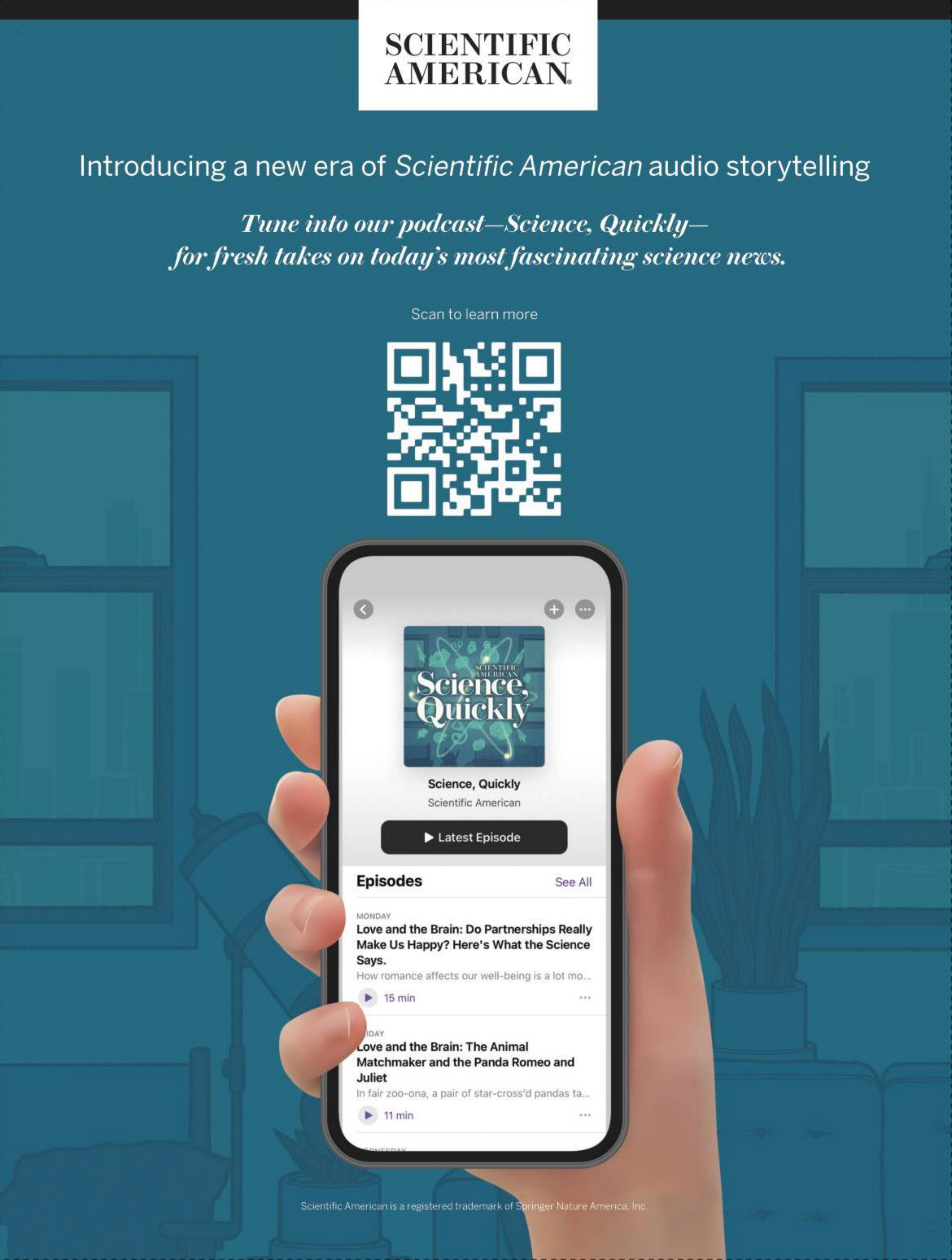
In scarce light, chloroplasts' glassy state lets them form a flat layer to soak up as much light as possible, like a cat in a patch of sun. But too much light is damaging, so in strong light conditions the chloroplasts weave and dodge to minimize exposure. "We often think of plants as not being very dynamic, but at the cellular level, they're as dynamic as any other living thing," says Roger Hangarter, a plant biologist at Indiana University Bloomington, who was not involved in the study.

Hangarter questions whether studies in *E. densa* can be generalized to other plants, whose chloroplasts' shape, size and movement vary. The authors plan to collaborate with molecular biologists in future studies to integrate that level of biological detail into their physics-inspired models.

—Allison Parshall

Elodea densa underwater

Ron Boardman/Minden Pictures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In fair zoo-ona, a pair of star-cross'd pandas ta...
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Marianne Karplus, a geophysicist and associate professor at the University of Texas at El Paso, is inspired to write poetry during her scientific field expeditions in the western U.S., the Himalaya and Antarctica. Her poems have been published in several literary magazines.

Confluence

When two rivers meet,
they sometimes hesitate to mix.
The murky sediment load carried by one
keeps its distance from
the clear blue-green of the other.
Each reflects the color
of the landscape it has carved,
sometimes with caution,
and sometimes with turbulence.

Steep canyon walls bear witness
and scars of the steady descent
of water molecules pulled by gravity,
eroding crystals and grains, thirsty clay particles
that tumble and drift in the flow.
The rivers emerge and meander
away from the rugged mountains
and toward each other,
beginning to unburden their loads.

The distinct paths become one,
and the denser stream ducks under,
hiding its sedimentary past
along the line of mixing,
where eddies test the waters.
Clouds and clarity
complement each other,
and, with time,
dispersion and blending
shift the current into balance.

Michael Warren/Getty Images

Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American*. She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

The "10,000 Steps" Gimmick

New research points to different daily step goals depending on age and fitness

By Lydia Denworth

In 2022 I averaged 9,370 steps a day. I know. I counted. Or rather my iPhone counted. I carried it everywhere—not so much to catch every call as to catch every step. My daily aim? Ten thousand steps. Because goals.

Yet the concept of taking 10,000 steps a day to maintain health is rooted not in science but in a marketing gimmick. In the 1960s a company in Japan invented an early pedometer. Because the Japanese character for "10,000" looks like a person walking, the company called its device the 10,000-step meter.

"It was just sort of a catchy phrase," says I-Min Lee, an epidemiologist at Harvard Medical School and Brigham and Women's Hospital in Boston. Taking that many steps daily is challenging but doable for many people. "Sure, if you get 10,000 steps, it seems like a good goal. But there was not really any basis to it."

Step-counting devices such as watches and phones came into widespread use only in the past two decades. Once they did, scientists needed to follow users for long periods to learn anything meaningful about the number of steps that affects mortality, cardiovascular fitness or anything else. And until recently, that hadn't happened.

The current physical activity guidelines from the U.S. Department of Health and Human Services, published in 2018, are still based on time. Experts reviewed hundreds of studies on exercise and health. Nearly all were based on self-reports of physical activity, a measure that is not exact. It's the equivalent of guessing how much time I spent walking last year.

Because of that room for error, the experts ended up recommending broad exercise ranges and not step counts: 150 to 300 minutes of weekly moderate activity (the equivalent of brisk walking) or 75 to 150 minutes of vigorous activity (for example, jogging) during the same period. A decade of consistently hitting that goal translates to about an extra year and a half of life, epidemiological studies indicate. There simply wasn't enough evidence to make a similar determination about steps. "It killed me that we couldn't," says William Kraus, a physician and scientist at Duke University, who helped to draw up the guidelines. "Step counts are accessible. People can understand them."

Now evidence about steps is starting to come in. In 2019 Lee published one of the first studies specifically investigating the actual effects of meeting the 10,000-step goal. Several other large studies followed. The result? Some movement is good, and more is better, but the benefits taper at some point. Your personal peak depends on your age. People younger than 60 should indeed walk 8,000 to 10,000 steps a day to get the best benefits in terms of life expectancy and cardiovascular health. People older than 60 show the most benefit between 6,000 and 8,000 steps. (Seven thousand to 9,000 steps a day is roughly equivalent to 150 to 300 minutes of brisk walking each week, the target in the 2018 guidelines.)

The difference is energy expenditure. "We basically relate energy expenditure to health outcomes," Kraus says. Walking for 60 minutes at 3.3 miles an hour and running for 30 minutes at six miles an hour use the same amount of energy. "The older you are, the less efficient you are with your steps," Kraus says. "Per step, older people expend more energy." As a result, they need fewer steps to achieve the same benefits.

Adding a few thousand steps a day can be especially meaningful for someone who isn't physically able to walk briskly, says Amanda Paluch, an epidemiologist at the University of Massachusetts Amherst, who led two meta-analyses linking step counts with risk of death and cardiovascular disease. She concludes that "the people who are the least active have the most to gain."

The total number of steps you take does appear to matter more than the speed at which you take them. "The relevant question for me is, When two people walk the same amount, does it matter whether their steps are accumulated at a faster rate versus a slower rate?" Lee says. The answer so far is no.

Newer studies are moving beyond death rates to ask questions about the way steps may contribute to diabetes prevention or help to control blood pressure and weight. The goal, after all, is not just to live longer but to live healthier. Full results are not in yet, so Lee's advice in the meantime is: "Tailor your steps according to what you are trying to achieve and according to who you are." SA

Illustration by Jay Bendt

Tech Talks to Animals

Portable sensors and artificial intelligence are helping researchers begin to talk back to nonhumans

By Sophie Bushwick

In the 1970s a young gorilla known as Koko drew worldwide attention with her ability to use human sign language. But skeptics maintain that Koko and other animals that "learned" to speak (including chimpanzees and dolphins) could not truly understand what they were "saying"—and that trying to make other species use human language, in which symbols represent things that may not be physically present, is futile.

"There's one set of researchers that's keen on finding out whether animals can engage in symbolic communication and another set that says, 'That is anthropomorphizing. We need to understand nonhuman communication on its own terms,'" says Karen Bakker, a professor at the University of British Columbia and a fellow at the Harvard Radcliffe Institute for Advanced Study. Now scientists are using improved sensors and artificial-intelligence technology to observe and decode how a broad range of species, including plants, already share information with their own methods. This field of "digital bioacoustics" is the subject of Bakker's 2022 book *The Sounds of Life: How Digital Technology Is Bringing Us Closer to the Worlds of Animals and Plants* (Princeton University Press).

Scientific American spoke with Bakker about how technology can help humans communicate with creatures such as bats and honeybees—and how these conversations are forcing us to rethink our relationship with other species.

[*An edited transcript of the interview follows.*]

Can you give us a brief history of humans attempting to communicate with animals?

There were numerous attempts in the mid-20th century to try to teach human language to nonhumans, primates such as Koko. And those efforts were somewhat controversial. As we look back, one view we have now (that may not have been so prevalent then) is that we were too anthropocentric in our approaches. The desire then was to assess nonhuman intelligence by teaching nonhumans to speak like we do—when in fact we should have been thinking about their abilities to engage in complex communication on their own terms, in their own embodied way, in their own worldview.

One of the terms used in the book is the notion of *umwelt,* which is this idea of the lived experience of organisms. If we are attentive to the *umwelt* of another organism, we wouldn't expect a honeybee to speak human language, but we would become very interested in the fascinating language of honeybees, which is vibrational and positional. It's sensitive to nuances such as the polarization of sunlight that we can't even begin to convey with our bodies. That is where the science is today. The field of digital bioacoustics—which is accelerating exponentially and unveiling fascinating findings about communication across the tree of life—is now approaching these animals and asking not "Can they speak like humans?" but "Can they communicate complex information to one another? How are they doing so? What is significant to them?" I would say that's a more biocentric approach, or at the very least it's less anthropocentric.

Taking a bigger view, I think it's also important to acknowledge that listening to nature, "deep listening," has a long and venerable tradition. It's an ancient art that is still practiced in an unmediated form. There are long-standing Indigenous traditions of deep listening that are deeply attuned to nonhuman sounds. So if we combine digital listening—which is opening up vast new worlds of nonhuman sound and decoding that sound with artificial intelligence—with deep listening, I believe that we are on the brink of two important discoveries. The first is language in nonhumans. And that's a very controversial statement, which we can dig into. The second is: I believe we're at the brink of interspecies communication.

What kind of technology is enabling these breakthroughs?

Digital bioacoustics relies on very small, portable, lightweight digital recorders, which are like miniature microphones that

Illustration by Irene Rinaldi

Sophie Bushwick is an associate editor covering technology at *Scientific American.*

scientists are installing everywhere from the Arctic to the Amazon. You can put these microphones on the backs of turtles or whales. You can put them deep in the ocean or on the highest mountaintop or attach them to birds. They can record continuously, 24/7, in remote places scientists cannot easily reach, even in the dark, and without the disruption that comes from introducing human observers in an ecosystem.

That instrumentation creates a data deluge, and that is where artificial intelligence comes in—because the same natural-language-processing algorithms that we are using to such great effect in tools such as Google Translate can also be used to detect patterns in nonhuman communication.

What's an example of these communication patterns?

In the bat chapter where I discuss the research of Yossi Yovel of Tel Aviv University, there's a particular study in which his team monitored [nearly two] dozen Egyptian fruit bats for two and a half months and recorded their vocalizations. They then adapted a voice-recognition program to analyze [15,000 of] the sounds, and the algorithm correlated specific sounds with specific social interactions captured via videos—such as when two bats fought over food. Using this, the researchers were able to classify the majority of bats' sounds. That is how Yovel and other researchers such as Gerry Carter of the Ohio State University have been able to determine that bats have much more complex language than we previously understood. Bats argue over food; they distinguish between genders when they communicate with one another; they have individual names, or "signature calls." Mother bats speak to their babies in an equivalent of "motherese." But whereas human mothers raise the pitch of their voices when talking to babies, mother bats lower the pitch—which elicits a babble response in the babies that learn to "speak" specific words or referential signals as they grow up. So bats engage in vocal learning.

That's a great example of how deep learning is able to derive these patterns from this instrumentation, all of these sensors and microphones, and reveal to us something that we could not access with the naked human ear. Because most of bat communication is in the ultrasonic, above our hearing range, and because bats speak much faster than we do, we have to slow it down to listen to it, as well as reduce the frequency. So we cannot listen like a bat, but our computers can. The next insight is that our computers can also speak back to the bat. The software produces specific patterns and uses those to communicate back to the bat colony or to the beehive, and that is what researchers are now doing.

How are researchers talking to bees?

The honeybee research is fascinating. A researcher named Tim Landgraf of Freie Universität Berlin studies bee communication, which, as I mentioned earlier, is vibrational and positional. When honeybees "speak" to one another, it's their body movements, as well as the sounds, that matter. Now computers, and particularly deep-learning algorithms, are able to follow this because you can use computer vision, combined with natural-language processing. They have now perfected these algorithms to the point where they're actually able to track individual bees, and they're able to determine what impact the communication of an individual might have on another bee. From that emerges the ability to decode honeybee language. We found that they have specific signals. Researchers have given these signals funny names. Bees toot; they quack. There's a "hush" or "stop" signal, a whooping "danger" signal. They've got piping [signals related to swarming] and begging and shaking signals, and those all direct collective and individual behavior.

The next step for Landgraf was to encode this information into a robot that he called RoboBee. Eventually, after seven or eight prototypes, he came up with a "bee" that could enter the hive, and it would essentially emit commands that the honeybees would obey. So Landgraf's honeybee robot can tell the other bees to stop, and they do. It can also do something more complicated, which is the very famous waggle dance—it's the communication pattern they use to convey the location of a nectar source to other honeybees. This is a very easy experiment to run, in a way, because you put a nectar source in a place where no honeybees from the hive have visited. You then instruct the robot to tell the honeybees where the nectar source is, and then you check whether the bees fly there successfully. And indeed, they do. This result happened only once, and scientists are not sure why it worked or how to replicate it. But it is still an astounding result.

This raises a lot of philosophical and ethical questions. You could imagine such a system being used to protect honeybees—you could tell honeybees to fly to safe nectar sources and not polluted ones that had, let's say, high levels of pesticides. You could also imagine this could be a tool to domesticate a previously wild species that we have only imperfectly domesticated or to attempt to control the behavior of other wild species. The insights about the level of sophistication and the degree of complex communication in nonhumans raise some very important philosophical questions about the uniqueness of language as a human capacity.

What impact is this technology having on our understanding of the natural world?

The invention of digital bioacoustics is analogous to the invention of the microscope. When Dutch scientist Antonie van Leeuwenhoek started looking through his microscopes, he discovered the microbial world, and that laid the foundation for countless future breakthroughs. So the microscope enabled humans to see anew with both our eyes and our imaginations. The analogy here is that digital bioacoustics, combined with artificial intelligence, is like a planetary-scale hearing aid that enables us to listen anew with both our prosthetically enhanced ears and our imagination. This is slowly opening our minds not only to the wonderful sounds that nonhumans make but to a fundamental set of questions about the so-called divide between humans and nonhumans, our relationship to other species. It's also opening up new ways to think about conservation and our relationship to the planet. It's pretty profound. SA

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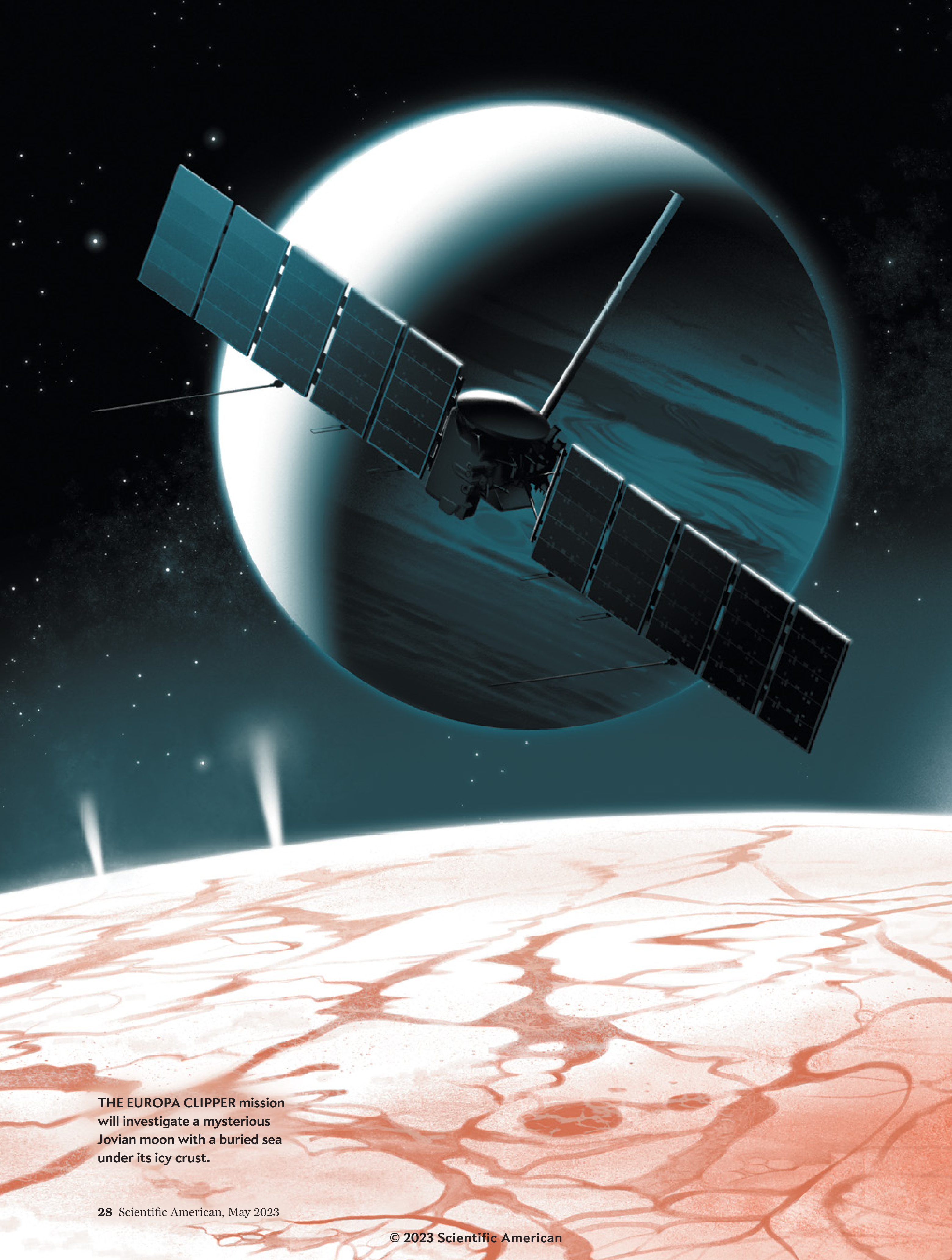


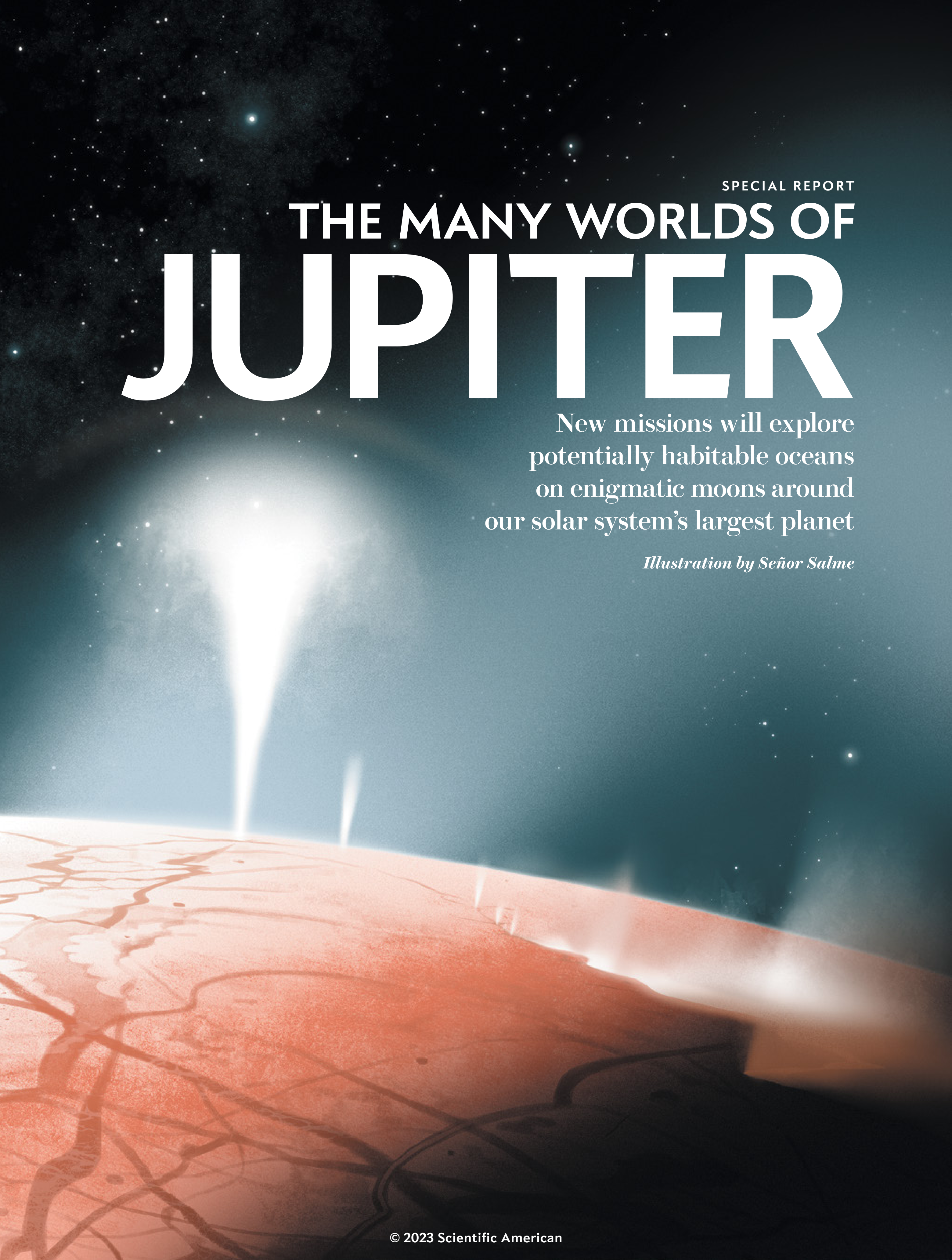
THE EUROPA CLIPPER mission will investigate a mysterious Jovian moon with a buried sea under its icy crust.

SPECIAL REPORT

THE MANY WORLDS OF JUPITER

New missions will explore potentially habitable oceans on enigmatic moons around our solar system's largest planet

Illustration by Señor Salme

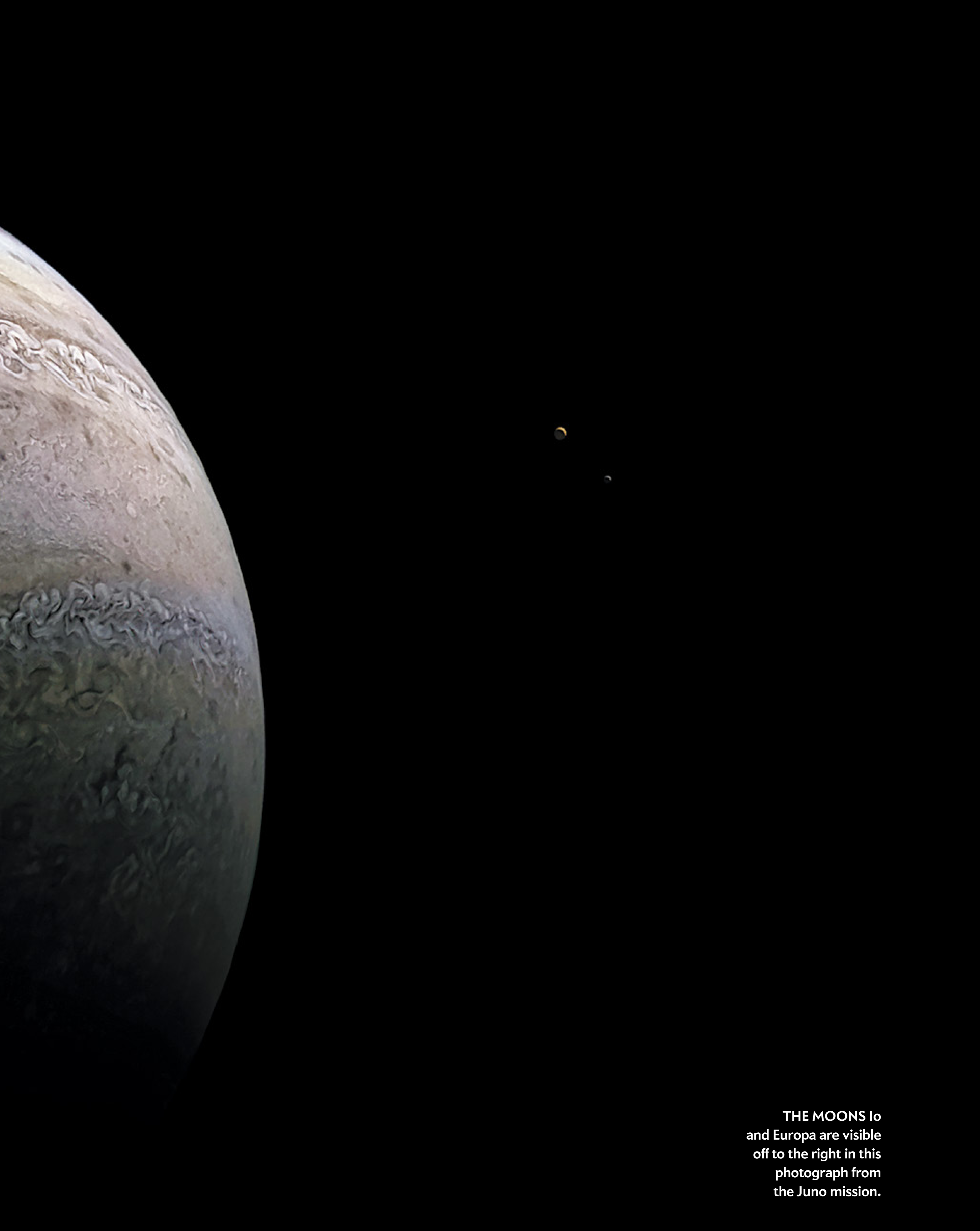


PLANETARY SCIENCE

MISSIONS TO THE MOONS

A new European spacecraft is the first of two probes that will hunt for signs of habitability on Jupiter’s icy satellites

By Jonathan O’Callaghan



THE MOONS Io and Europa are visible off to the right in this photograph from the Juno mission.

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.

IF THERE IS LIFE ELSEWHERE IN OUR SOLAR SYSTEM, JUPITER'S LARGE ICY MOONS ARE A PRETTY GOOD bet on where to find it.

Scientists believe vast oceans lurk within them, kept liquid by the jostling from Jupiter's immense gravitational field and protected from the planet's harsh radiation belts by thick ice sheets. "What we've learned on Earth is where you find water, you quite often find life," says Mark Fox-Powell of the Open University in England. "When we look out in the solar system, places that have [liquid] water in the present day are really restricted to Earth and the moons of Jupiter and Saturn." That last planet and its satellites, studied in detail by NASA and the European Space Agency's Cassini-Huygens mission from 2004 to 2017, still hold secrets that scientists will one day probe. For now all eyes are on Jupiter.

A new mission to visit our solar system's largest planet and investigate the habitability of its moons is now set to begin. ESA's JUICE—the Jupiter Icy Moons Explorer—was shipped to French Guiana in South America for its April launch on a European Ariane 5 rocket. The six-ton JUICE spacecraft will take eight years to reach Jupiter, saving fuel along the way by using gravitational assists from Earth, Venus and Mars. On its arrival in July 2031 the solar-powered machine will focus its 10 science instruments on three of the four largest Jovian moons—Europa, Ganymede and Callisto—all thought to harbor subsurface oceans. Ganymede, the solar system's largest moon, will receive most of JUICE's attention. After its initial reconnaissance, the spacecraft will enter orbit there in 2034. "We're trying to characterize what the habitability of Ganymede might be," says Emma Bunce of the University of Leicester in England, part of the JUICE team.

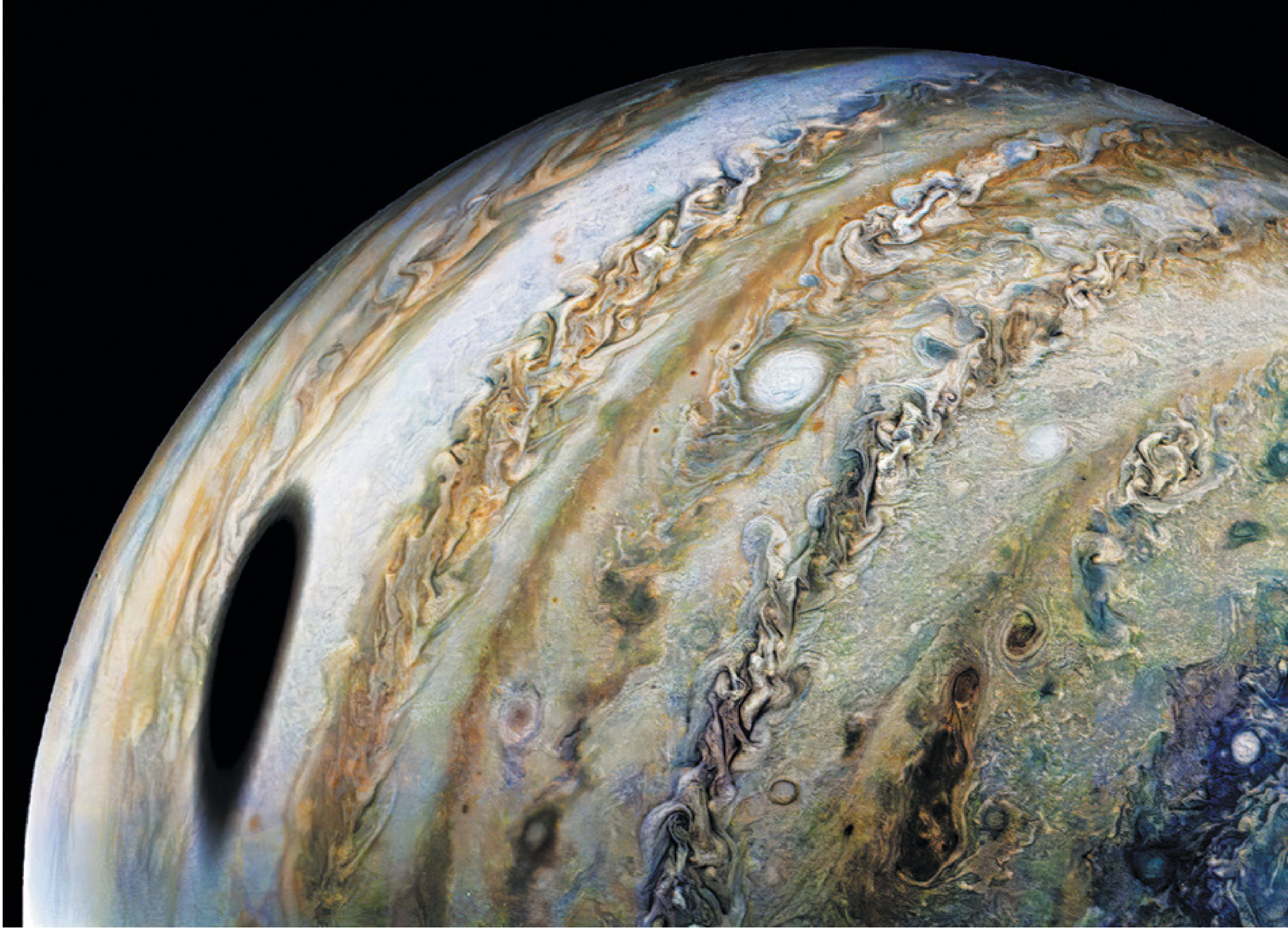
ESA isn't the only space agency with Jupiter in its sights. The concept that would ultimately become JUICE emerged in 2008 as part of the Europa Jupiter System Mission (EJSM), a joint venture with NASA. This collaborative effort called for Europe to build a Ganymede-focused spacecraft, while NASA would construct a probe for Europa. Funding issues in the U.S., however, led NASA to pull the plug on EJSM in the early 2010s, leaving Europe flying solo. "We didn't have the money," says Louise Prockter of the Johns Hopkins University Applied Physics Laboratory, part of the U.S. proposal team. "That killed the Europa part." The situation was disappointing but not wholly unexpected. "These things happen," says Michele Dougherty of Imperial College London, who worked on the European side of EJSM.

Redemption came in 2013, when NASA's efforts to explore Europa received renewed support and funding from Congress. Initially named the Europa Multiple Flyby Mission, the U.S. project eventually became Europa Clipper, after the "clipper" merchant ships of the 19th century. The international collaboration was reborn, mostly. "It's much reduced," Prockter says, although she estimates about 70 percent of the originally planned joint science will still be possible. With these two missions, our knowledge of Jupiter and its moons is set to increase substantially. The spacecraft will tell us whether life could exist in some of these worlds' bewildering subsurface oceans, laying the groundwork for later missions to look directly for evidence of such life, possibly even by diving into the oceans themselves. We can't yet travel to alien worlds around other stars, but Jupiter might offer the next best thing.

THE FIRST MOONS

THE JOVIAN ARENA is often regarded as a miniature solar system because of the complexity and variety of the planet's moons—particularly its four largest, the Galilean moons, named for Italian astronomer Galileo Galilei, who discovered them in 1610. Their identification shook people's understanding of the universe, revealing the first known objects orbiting a body that was not the sun or Earth and thereby validating the Copernican model of the cosmos, which did not have us at its center. Jupiter is now known to have 92 natural satellites. Yet even Galileo might not have appreciated how fascinating his moons would turn out to be 400 years later or how pivotal they might prove in the hunt for life elsewhere in the universe.

The first spacecraft to venture into Jupiter's realm, moons and all, was NASA's Pioneer 10 spacecraft. It flew past the planet in December 1973, providing our first close-up images of the magnificent gas giant. The flyby of NASA's Voyager 1 spacecraft in March 1979 proved even more remarkable. The spacecraft's images of the moon Europa revealed that it had a bright, icy surface devoid of



craters, hinting that some kind of resurfacing process was keeping its crust fresh and unblemished. The best bet was an unseen reservoir of liquid water below the surface, scientists surmised—an enticing option given that on Earth, life follows water.

In December 1995 NASA's Galileo mission became the first to orbit Jupiter, making numerous discoveries—for example, that the planet's third-largest moon, Io, is the most volcanically active world in the solar system. Data that Galileo took at Europa in 1996 found that something was disrupting Jupiter's magnetic field, offering stronger hints of a liquid sloshing under Europa's surface. The best evidence for a liquid ocean on Europa came two decades later, when the Hubble Space Telescope spotted plumes of water escaping from the moon's surface. The Galileo spacecraft orbited Jupiter for eight years, ending in 2003, and was "a fantastic mission," says Olivier Witasse of ESA, the project scientist for JUICE. "We are really going on the shoulders of Galileo."

No other probe would orbit Jupiter until the arrival of NASA's Juno spacecraft in 2016. Juno is still operational today, but it is focused on Jupiter itself, swinging past it in a looping orbit to probe the planet's interior, image its violent storms and monitor its immense magnetic field. The spacecraft has taken some images of Jupiter's moons, but it'll take dedicated missions to really expose their secrets. And that's where JUICE and Clipper come in.

MOON HOPPING AND PLUME SPOTTING

CLIPPER WILL LAUNCH in fall 2024 on a SpaceX Falcon Heavy rocket. Despite its later launch date, its more powerful launch vehicle

THE SHADOW of the moon Ganymede hangs over Jupiter in this image from Juno, with color enhancement by a citizen scientist.

will allow the spacecraft to reach Jupiter more than a year before JUICE, in April 2030. It will not orbit Europa like JUICE will Ganymede, because Europa's proximity to Jupiter places it perilously deep within the planet's radiation belts. Instead Clipper will perform about 50 Europa flybys as it zips around the Jovian system, allowing it to map the moon's interior and work out the extent of its subsurface ocean while also studying other targets. "Putting an orbiter around Europa, because of the radiation environment, means you're only going to survive one to three months before the radiation kills you," says Curt Niebur, Europa Clipper program scientist at NASA Headquarters in Washington, D.C. "We realized instead we could fly by, collect our data and get the heck out of town where the radiation is lower. That way we can last years, not months."

During their overlapping missions, JUICE and Clipper will perform an intricate tango as they hop between Jupiter's attractions, with copious opportunities for collaboration. "To have two spacecraft in the same system will be really fantastic," Witasse says. About 20 scientists from both missions are meeting virtually every week as part of the JUICE-Clipper Steering Committee, with the group formulating ideas for how the two spacecraft might sync up at Jupiter. "We're busy talking through the science opportunities and coming up with a plan" to present to NASA and ESA, says Bunce, who co-chairs the committee with Prockter. Whereas "some of the

NASA/JPL-Caltech/SwRI/MSSS (*image data*); Thomas Thomopoulos © CC BY 3.0 Unported (https://photojournal.jpl.nasa.gov/catalog/PIA25015) (*image processing*)

IN 2021 JUNO made a close flyby of Ganymede, the solar system's largest moon.

NASA/JPL-Caltech/SwRI/MSSS *(image data)*; Kalleheikki Kannisto © CC BY 3.0 Unported (https://photojournal.jpl.nasa.gov/catalog/PIA25028) *(image processing)*

details are a little bit different" from the initial EJSM collaboration, Bunce says, the overall dream remains alive. "The original plan was one mission focused on Ganymede and another mission focused on Europa," she says. "And that's what we've got."

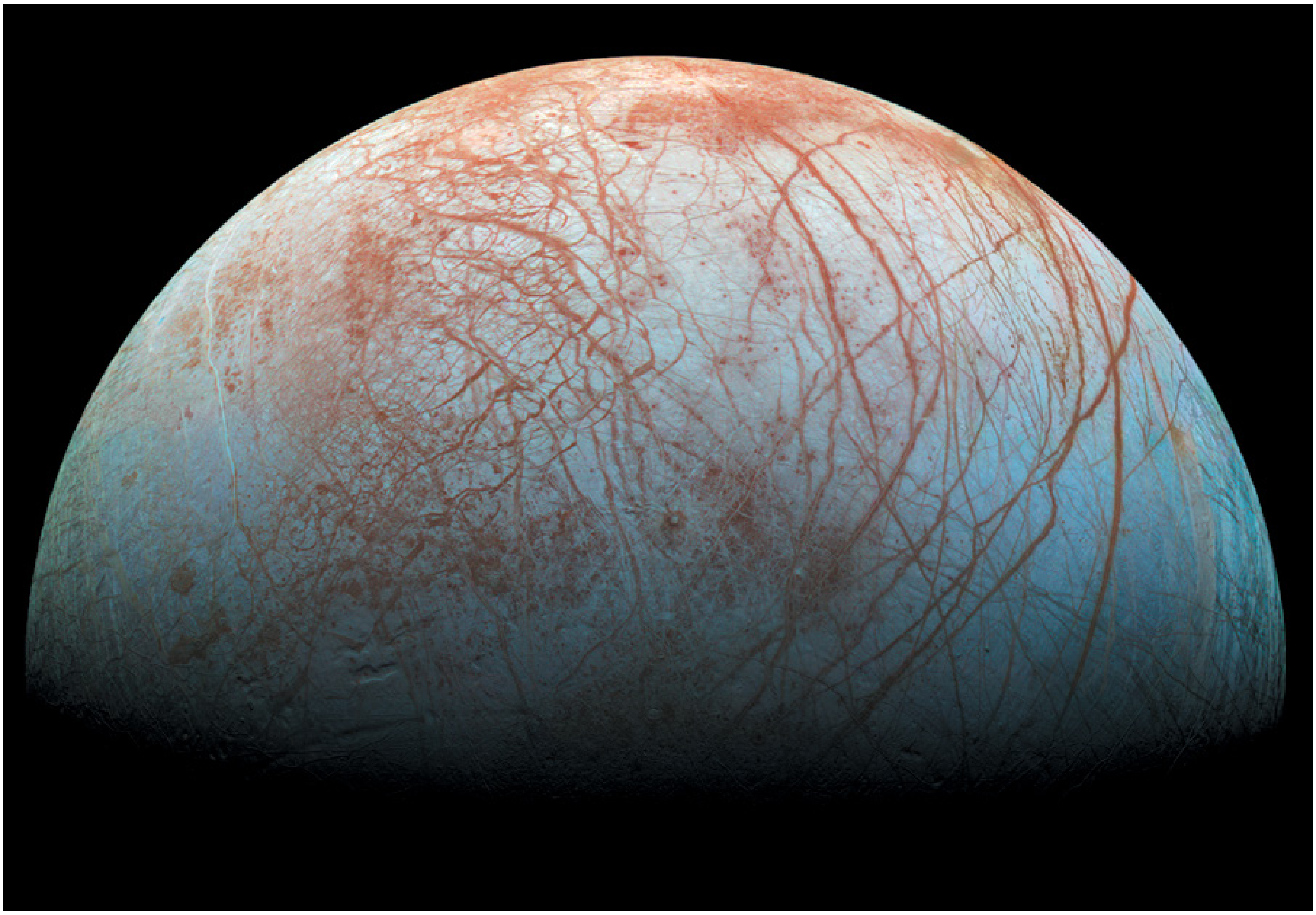
One possibility is that each spacecraft could act as a spotter for the other. JUICE, for example, could keep an eye on Europa from afar as Clipper prepares to swoop past—a valuable partnership, especially if there are indeed plumes of liquid water spouting from cracks in the overlying ice. Peering into these plumes could lead to studying oceanic ejecta that are just "minutes old," Fox-Powell says. "It really gives us an opportunity to study something that's pristine." As Clipper approaches Europa, JUICE could look for plumes erupting from the surface, allowing Clipper to train its eye in that direction. "If JUICE spotted one, that could tell us where to look," Prockter says. Clipper may even fortuitously pass through some plumes, allowing it to directly sample them and look for signs of complex molecules that might hint at signs of life in the Europan ocean.

JUICE will perform two Europa flybys of its own prior to orbiting Ganymede. The one in July 2032 will be just four hours apart from a Clipper flyby. "We can make similar measurements at the same time," Witasse says. That could allow some exciting science to be done, although the exact details have yet to be determined. "We won't fly over the same location, but it will for sure be very interesting," he adds. "We could image similar surface features, or if there is a plume, we can observe it from different geometries."

The joint emphasis on Europa is partially based on scientists' suspicions that the moon's liquid-water ocean is in direct contact with a rocky core. There hydrothermal vents—openings in the seafloor where heat from deeper within can escape—could supply sufficient energy and nutrients to sustain life. "On Earth we have hydrothermal vents where there are whole communities of organisms," Fox-Powell says. "We have good reason to believe that similar kinds of chemical reactions are going on at Europa." Ganymede's much larger bulk, however, means that higher-density ice may have sunk to the bottom of its ocean, forming a vent-blocking barrier. "It could seal the rocky core away," Fox-Powell says. "Europa is not big enough to have that amount of gravity and pressure, so that high-pressure ice doesn't form."

TWO MISSIONS, ONE VISION

NONE OF THIS RULES OUT Ganymede's chances of habitability, nor does it diminish that moon's scientific interest. After entering orbit around Ganymede in December 2034, JUICE will survey the entire surface, study the moon's magnetic field and attempt to map its aquatic inner layers. For an environment to be interesting for potential habitability, it needs "a heat source, liquid water, organic material and stability," Dougherty says. "At [Saturn's moon] Enceladus we know we've got three. At Europa we've got three. And at Ganymede we're trying to find out." Although it will start in a high orbit 5,000 kilometers above Ganymede, during a nine-month period JUICE will lower its altitude to just 200 kilometers over the moon's surface. Eventually, at the mission's end in 2035, the spacecraft will be deliberately crashed into the surface to minimize the chance of any debris contaminating Europa. Ganymede is not thought to have plume activity, but if it does or if its ice crust is found to be particularly thin, this finale may have to be rethought so as not to contaminate Ganymede's liquid ocean, too. "If there is something that indicates a connection with the inner ocean and the


NASA/JPL-Caltech/SETI Institute

CRACKS AND RIDGES crisscross the surface of Europa in an image assembled from data taken by the Galileo spacecraft.

outer surface, we may need to change our orbit," says Giuseppe Sarri of ESA, project manager for JUICE.

Clipper will provide a similar level of knowledge about Europa and its ocean. It is not designed to find definitive evidence of life, however; at best, it will perhaps see the ingredients of life within the moon's plumes. Life detection may come on a later mission, such as NASA's much sought-after Europa Lander. A concept for the mission was drawn up years ago by scientists and engineers at NASA's Jet Propulsion Laboratory in California, but it awaits further funding. "Europa Lander has not been in the president's budget or the budget passed by Congress for a while," Niebur says. A road map for U.S. interplanetary exploration produced by the U.S. National Academies in late 2021, meanwhile, placed a Europa Lander mission as a lower priority for NASA than other projects.

For now the work is archived, ready and waiting to be reborn. "I'm confident that what Europa Clipper will learn will make us want to go back, and a lander of some kind is the logical next step," Niebur says. "But maybe Clipper will throw us a curveball, and a lander is not the right way to go. Maybe we'll want to hover in the plumes instead of landing."

If scientists do want to take a dip in this alien ocean, breaking through the kilometers-thick ice poses its own challenges. One possibility is that a lander could include a heat probe to melt its way through the frozen crust. Last year Paula do Vale Pereira, now at the Florida Institute of Technology, led an experiment to see how long that might take, using a two-meter-high column of cryogenic ice called the Europa Tower to simulate the Europan surface. Presenting her work at the 241st meeting of the American Astronomical Society in Seattle in early January 2023, she found the task might take anywhere between three and 13 years—long times to wait, even for multidecadal missions to the outer solar system.

Besides the ticking of the clock, other obstacles abound. "Figuring out a way to have cables transfer power and information between the lander and the probe is a big, big problem that needs to be solved in the coming years," do Vale Pereira says. The lander would have to carry perhaps several kilometers' worth of cable with it, and the cable would have to be resilient enough to endure water refreezing as ice around it during the probe's descent. The scientific value in solving such problems, however, is tremendous, not least the prospect of placing some kind of machine directly inside an alien ocean.

Such dreams are many years away. Any hope of making them a reality hinges on voyaging to Jupiter and confirming its icy moons are the attractive targets we believe them to be. Beginning with JUICE in April and Clipper next year, we are set to solve some of the most intriguing questions about Jupiter's moons that have long gone unanswered. The Galileo spacecraft "revealed to us that it's worth going back," Niebur says. Now we're doing so with not one but two spacecraft—a transatlantic partnership to significantly advance the search for habitability around our sun. There is no world in our solar system quite like Earth, but perhaps places like Europa and even Ganymede are a close second. If life can survive here, who knows where else it might thrive? SA

Rebecca Boyle is an award-winning freelance journalist in Colorado. Her forthcoming book *Our Moon: How Earth's Celestial Companion Transformed the Planet, Guided Evolution, and Made Us Who We Are* (Random House) will explore Earth's relationship with its satellite throughout history.

Juan Velasco is founder of the award-winning information design studio 5W Infographic (www.5wgraphics.com). He is a former art director of *National Geographic* and the *New York Times*.

PLANETARY SCIENCE

ALIEN OCEANS

Six moons of the outer solar system may hold vast amounts of liquid water and, with it, life

By Rebecca Boyle

Graphics by 5W Infographic

IN 2005 THE CASSINI SPACECRAFT VISITING SATURN FLEW THROUGH something engineers didn't expect—a fine water mist, spraying into space at 1,290 kilometers per hour through cracks in the surface of Saturn's tiny, ice-covered moon Enceladus. Cassini wasn't designed to sample the water, but the discovery inspired scientists to develop new missions to the outer solar system's icy moons. At least six of those worlds—two orbiting Saturn, three orbiting Jupiter and one by Neptune—might host watery oceans, sandwiched between a warm planetary core below and ice crust above.

On Earth, water is required for life "as we know it." Other than the dunes of Mars, where we have searched for half a century, astrobiologists now consider the icy moons of the outer planets some of the best places to look for life in our solar system.

The European Space Agency's Jupiter Icy Moons Explorer, nicknamed JUICE, was scheduled to launch in April toward the gas giant and its moons Europa, Callisto and Ganymede. JUICE and NASA's Europa Clipper mission to Jupiter and Europa, set to launch in 2024, will change our understanding of the outer solar system. The icy moons may rewrite our cosmic perspective, just as they did when astronomers discovered them in the 17th century.

"The outer solar system is probably replete with moons that could have liquid water oceans on them, and a subset could have geothermal and water-rock interactions on the bottom," says Chris German, an oceanographer at the Woods Hole Oceanographic Institution, who is co-leading a NASA-funded initiative called Network for Ocean Worlds (NOW). Why do those characteristics matter? "Everywhere that has those on our planet gets colonized by microbial life," German says.

Life could flourish in half-frozen slush on Europa and Enceladus, within the subsurface saltwater ocean of Ganymede, underneath the methane and ethane rivers of Titan, and maybe in brines in the deepest craters of the dwarf planets Ceres and Pluto. The icy shells of the ocean worlds may even contain pores filled with liquid water—and perhaps microbes, says Mike Malaska, an astrobiologist at NASA's Jet Propulsion Laboratory.

About two and a half kilometers into Greenland's ice sheet, pressure conditions mimic the top of the ice layer on moons like Europa, and microbe concentrations there are comparable to those in a spoonful of yogurt. Chemical interactions or geologic activity could provide energy for these life-forms, much as deep-sea volcanic vents like those German has discovered provide energy for extremophiles on Earth. "Pick your scenario for the origin of life on Earth, and it could have happened on Europa," says Steve Vance, an astrobiologist at JPL. Investigators might readily find organisms by using techniques for studying extreme life on our own planet.

NOW is led by scientists at Woods Hole, the Southwest Research Institute, the Desert Research Institute and Stanford University. It will host its first joint retreat in August, aiming to bring together astrobiologists and oceanographers in the search for biological beings. Co-leader Alison Murray, a microbial ecologist at the Desert Research Institute, first considered life on alien moons while studying a frozen hypersaline Antarctic lake called Lake Vida. She says that having experience in Earth's watery environments is essential to understanding those across the solar system. "We are actually going to go to places where we think life might be existing today," Murray says. "Did life evolve there? Did life *go* there?" To find out, we just need to take a deeper dive.

FROM OUR ARCHIVES

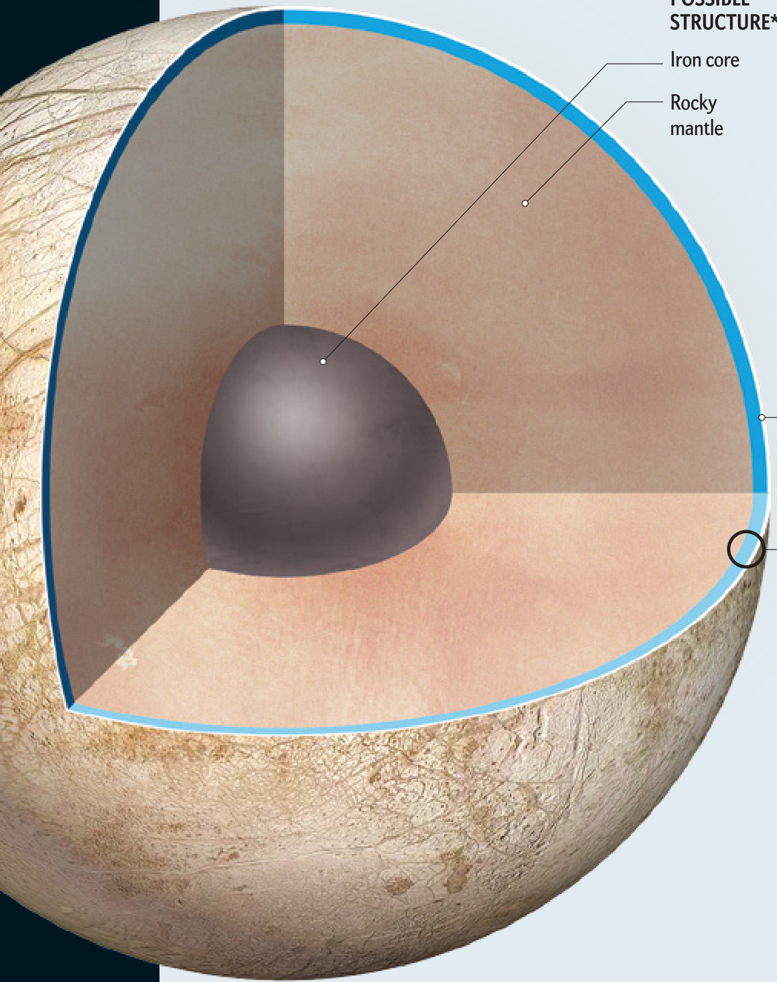
The Galileo Mission. Torrence V. Johnson; December 1995.

scientificamerican.com/magazine/sa

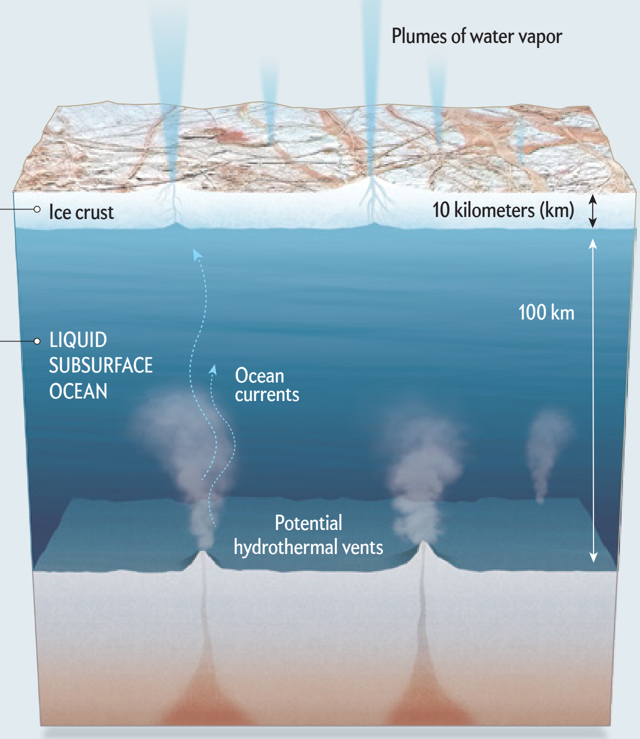
Europa

The Galileo spacecraft discovered that Europa might be venting thin plumes of water 160 kilometers into space. It also found that Jupiter's magnetic fields induced a current, indicating salty liquid water was present within the sphere. Europa is the solar system's smoothest object, suggesting its surface is remade by interior processes more frequently than most other worlds besides Earth.

STRONG EVIDENCE OF LIQUID-SALTWATER SUBSURFACE OCEAN



Blocks of ice may be rafting on top of an ocean slurry. The rocky seafloor may be covered in high-pressure ice-VII, which forms a cubic crystalline structure, unlike the hexagonal water ice on Earth. Ice-VII can efficiently transport salts, so it could support chemical interactions that could energize a web of life.



WHAT WE STILL DON'T KNOW

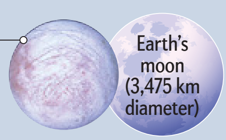
The Hubble Space Telescope saw fleeting evidence of water plumes escaping Europa through cracks in its icy shell. The upcoming Europa Clipper spacecraft has ice-penetrating radar, and its imaging spectrometer could reveal organic molecules, ammonia, high-pressure ices and even brine pools deep in the interior.

OCEAN VOLUME (billions of km³): Earth 1.8; Europa 2.6

DISCOVERED
1610 by Galileo Galilei

DIAMETER
3,130 KM

SURFACE TEMPERATURE
–225 °F



EXPLORED BY
1970s: Flybys of Pioneer 10, Pioneer 11, Voyager 1, Voyager 2
1996: Galileo

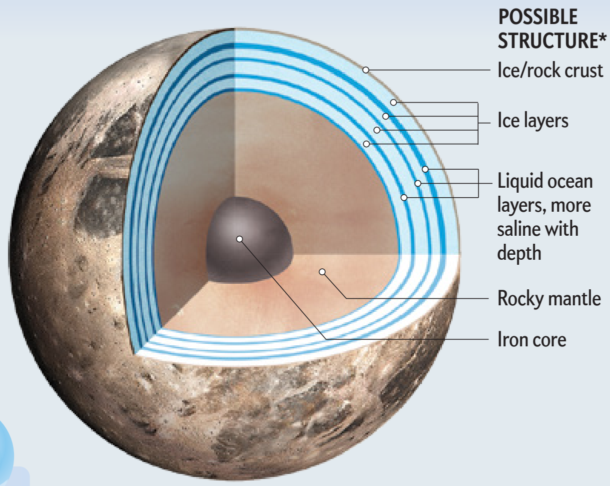
PLANNED MISSIONS
April 2023: European Space Agency's JUICE
2024: NASA's Europa Clipper

*Layers are not drawn to scale

NASA Visualization Technology Applications and Development (VTAD) (*Europa and Ganymede exteriors*), NASA/JPL-Caltech/SETI Institute (*Europa surface texture*), NASA/JPL/DLR (*Callisto exterior*)

Ganymede

The largest moon in our solar system might contain several layers of rock, water and exotic high-pressure ices. Interactions between rock and water are fundamental to microbial diversity on Earth. Ganymede is the only known moon with its own magnetic field, which causes auroras akin to those on Earth. The auroras sway when Jupiter's magnetic field fluctuates, partial evidence for a large saltwater ocean.



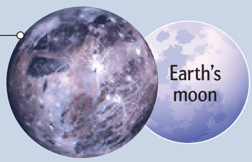
STRONG EVIDENCE OF LIQUID-SALTWATER SUBSURFACE OCEAN

OCEAN VOLUME (billions of km³): 1.8 Earth; 37.8 Ganymede

WHAT WE STILL DON'T KNOW

Ganymede is the JUICE mission's primary target. Scientists will use the spacecraft to try to determine the source of the moon's magnetic field and to study details about its auroras.

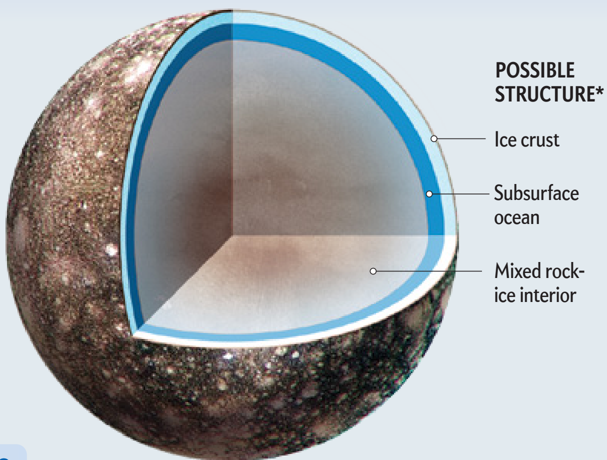
- **DISCOVERED**
  1610 by Galileo Galilei
- **DIAMETER**
  5,262 KM
- **SURFACE TEMPERATURE**
  −297 °F TO −171 °F



- **EXPLORED BY**
  1970s: Flybys of Pioneer 10, Pioneer 11, Voyager 1 and Voyager 2
  1996: Galileo **2000:** Cassini **2021:** Juno
- **PLANNED MISSIONS**
  April 2023: European Space Agency's JUICE

Callisto

Callisto is the least dense of Jupiter's moons. It has the good fortune of orbiting 1.8 million kilometers from the planet, beyond Jupiter's intense radiation belts. Because Jupiter's gravitational field is weaker at this distance, Callisto also experiences less tidal friction than its companion moons. The moon's heavily cratered surface suggests it has not been geologically active since its formation, so it might preserve a record of the primordial solar system.



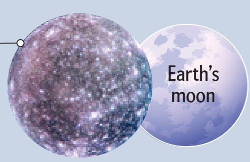
POTENTIAL LIQUID SUBSURFACE OCEAN

OCEAN VOLUME (billions of km³): 1.8 Earth; 4.8 Callisto

WHAT WE STILL DON'T KNOW

Scientists are split on whether Callisto hosts an underground saltwater ocean and how deep it would be. By using JUICE to study the moon's shape and its gravity field, scientists hope to settle this debate.

- **DISCOVERED**
  1610 by Galileo Galilei
- **DIAMETER**
  4,820 KM
- **SURFACE TEMPERATURE**
  −218 °F

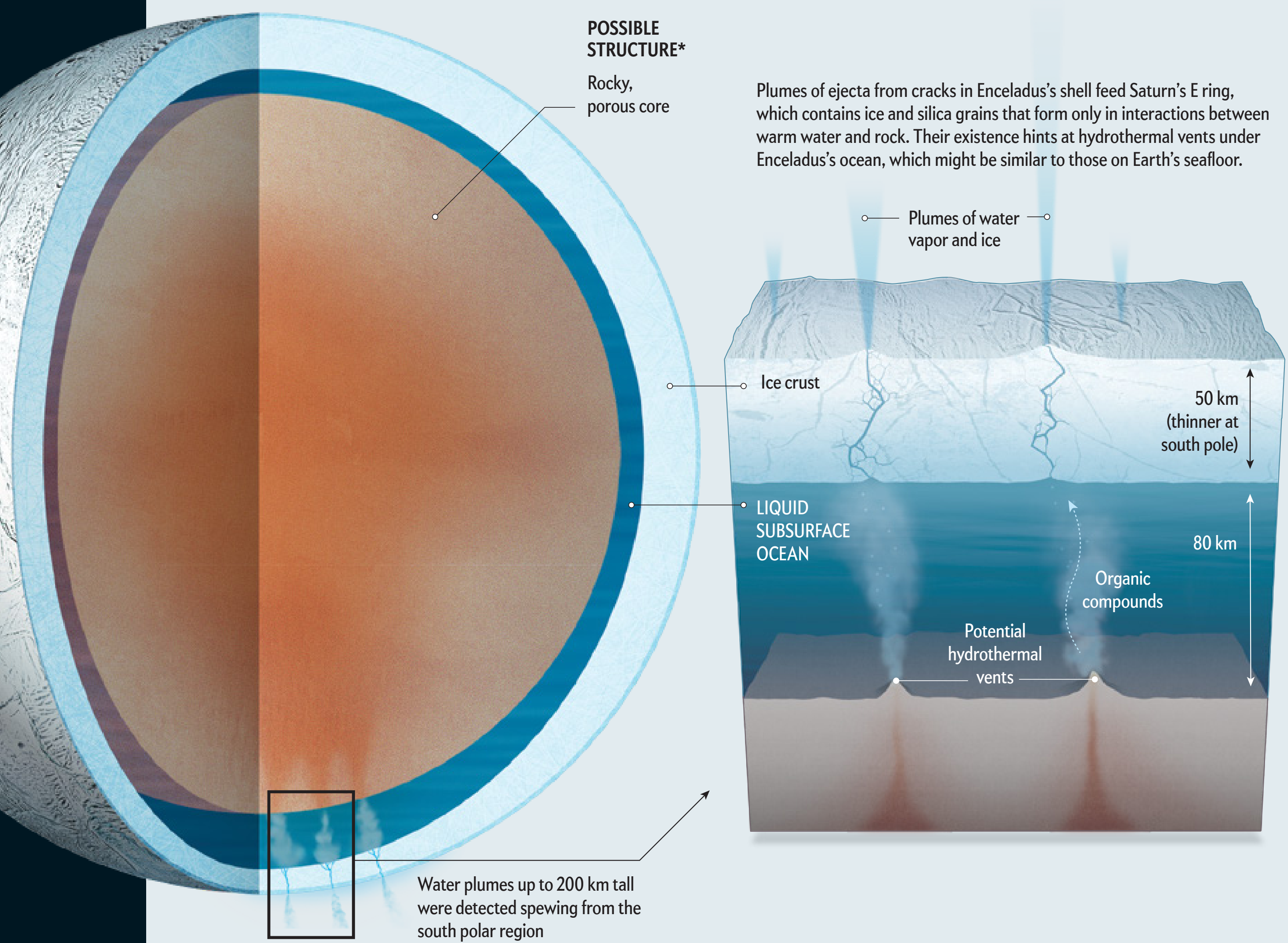


- **EXPLORED BY**
  1970s: Flybys of Pioneer 10, Pioneer 11, Voyager 1 and Voyager 2
  1996: Galileo
- **PLANNED MISSIONS**
  April 2023: European Space Agency's JUICE

Enceladus

Tiny Enceladus is the most reflective object in the solar system. Plumes of mist emanating from the outer shell freeze and fall back to the surface, keeping it snowy white. It is smooth like Europa, further evidence that it is geologically active today. Because the mist generates Saturn's second-outermost band—the E ring—sampling the band is a way to sample Enceladus's putative ocean and to search for organic molecules, amino acids or other ingredients for life.

STRONG EVIDENCE OF LIQUID-SALTWATER SUBSURFACE OCEAN



OCEAN VOLUME (billions of km³): 1.8 Earth; 0.01 Enceladus

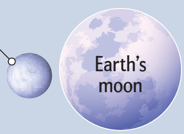
WHAT WE STILL DON'T KNOW

Scientists don't know the size of Enceladus's ocean, but the moon may be one of the easiest to investigate because spacecraft can detect elements in its plumes as well as in Saturn's E ring.

DISCOVERED
1789
by William Herschel

DIAMETER
504 KM

SURFACE TEMPERATURE
−330 °F



EXPLORED BY
1980–81: Flybys by Voyager 1 and Voyager 2
2005: Cassini

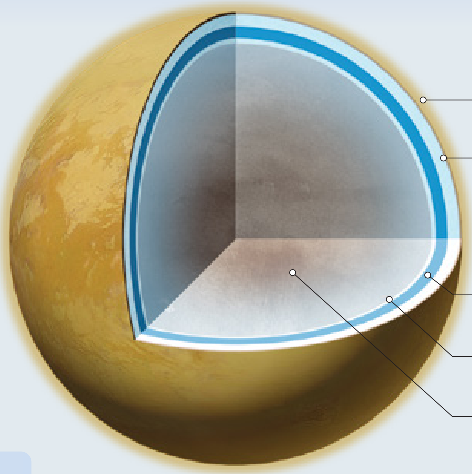
PLANNED MISSIONS
Enceladus Orbilander concept by Johns Hopkins Applied Physics Laboratory would orbit and then land in search for potential life

**Layers are not drawn to scale*

NASA/JPL-Caltech (*Enceladus exterior*), NASA/JPL-Caltech/University of Nantes/University of Arizona (*Titan exterior*), NASA Visualization Technology Applications and Development (VTAD) (*Triton exterior*)

Titan

Cassini dropped a lander on Titan, the alien world most like Earth, with vast plains and canyonlands. It settled on a plain made of ice grains and found evidence for great hydrocarbon lakes. Titan's dense atmosphere is mostly nitrogen, like Earth's, but lacks oxygen. It has abundant liquid methane and ethane, which create the moon's hazy orange cast. The compounds have a circulation cycle like water does on Earth that could support methane-based life.



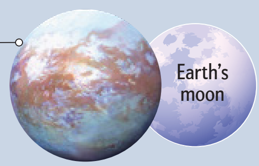
STRONG EVIDENCE OF LIQUID SUBSURFACE OCEAN

OCEAN VOLUME (billions of km³): 1.8 Earth · 17.0 Titan

WHAT WE STILL DON'T KNOW

One theory for why Titan hosts so much methane—which continually breaks down in sunlight—is that methane might erupt from cryovolcanoes that ooze chilled water instead of molten rock.

- **DISCOVERED**
  1655 by Christiaan Huygens
- **DIAMETER**
  5,152 KM
- **SURFACE TEMPERATURE**
  –290 °F

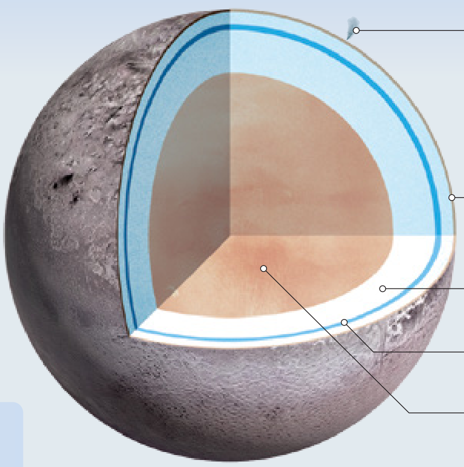


- **EXPLORED BY**
  1980–81: Flybys by Voyager 1 and 2
  2005: Cassini-Huygens (Cassini flybys and Huygens probe landing)
- **PLANNED MISSIONS**
  Mid-2030s: Dragonfly is set to launch in 2027 and arrive in 2034

MOON OF NEPTUNE

Triton

The largest Neptunian moon orbits in a retrograde motion and was most likely captured from the icy Kuiper belt, a distant asteroid ring. The wrenching change in the moon's trajectory probably heated it up, perhaps enough to warm a global ocean below the crust. Seasonal heating from the sun also warms the moon ever so slightly, even at 4.5 billion kilometers.



HYPOTHESIZED LIQUID SUBSURFACE OCEAN

OCEAN VOLUME (billions of km³): 1.8 Earth · 0.03 Triton

WHAT WE STILL DON'T KNOW

Voyager 2 glimpsed evidence of geysers and lavalike flows above Triton's surface, suggesting the presence of an ocean under a geologically active, icy crust. A closer look would help explain what is going on.

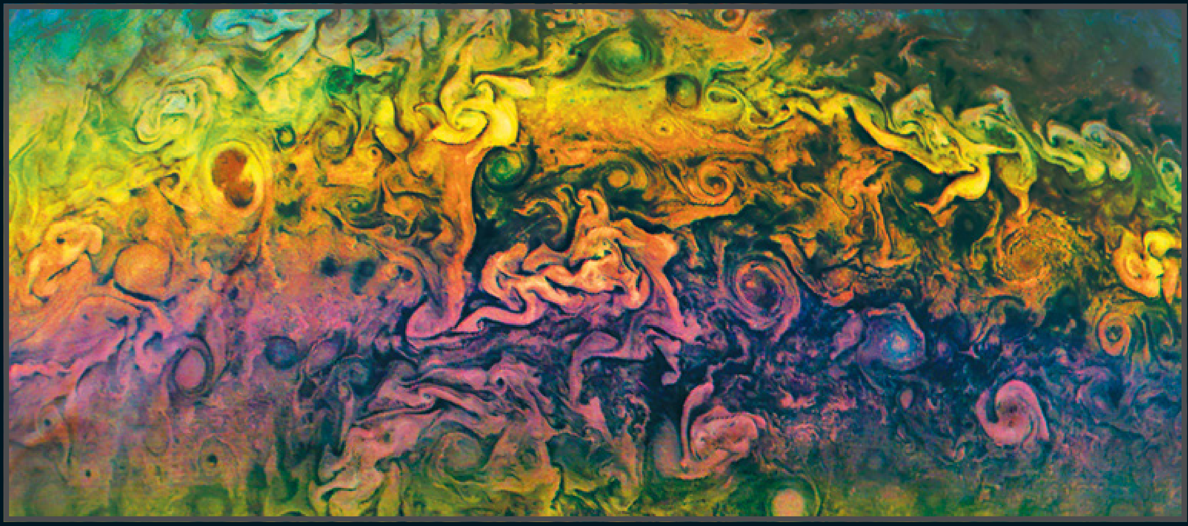
- **DISCOVERED**
  1846 by William Lassell
- **DIAMETER**
  2,704 KM
- **SURFACE TEMPERATURE**
  –391 °F

- **EXPLORED BY**
  1989: Flyby by Voyager 2
- **PLANNED MISSIONS**
  None planned so far

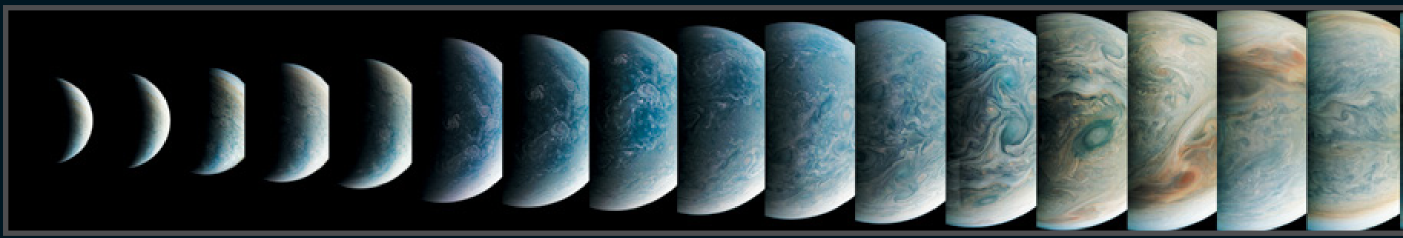
PLANETARY ART

Citizen scientists blend creativity and research using data from a dedicated camera on NASA's Juno probe

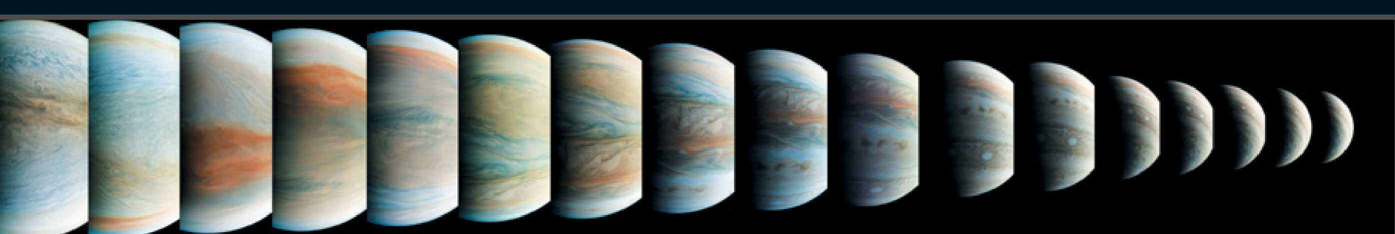
JUPITER'S STORMS recall Vincent van Gogh's *The Starry Night* in a processed image.



ADDED COLOR and effects highlight cyclones at Jupiter's northern pole.



AN EXAGGERATED elevation model shows, in a composite image, what the moon Europa might look like to a nearby visitor.



A MONTAGE shows the changing faces of Jupiter's atmosphere over time.

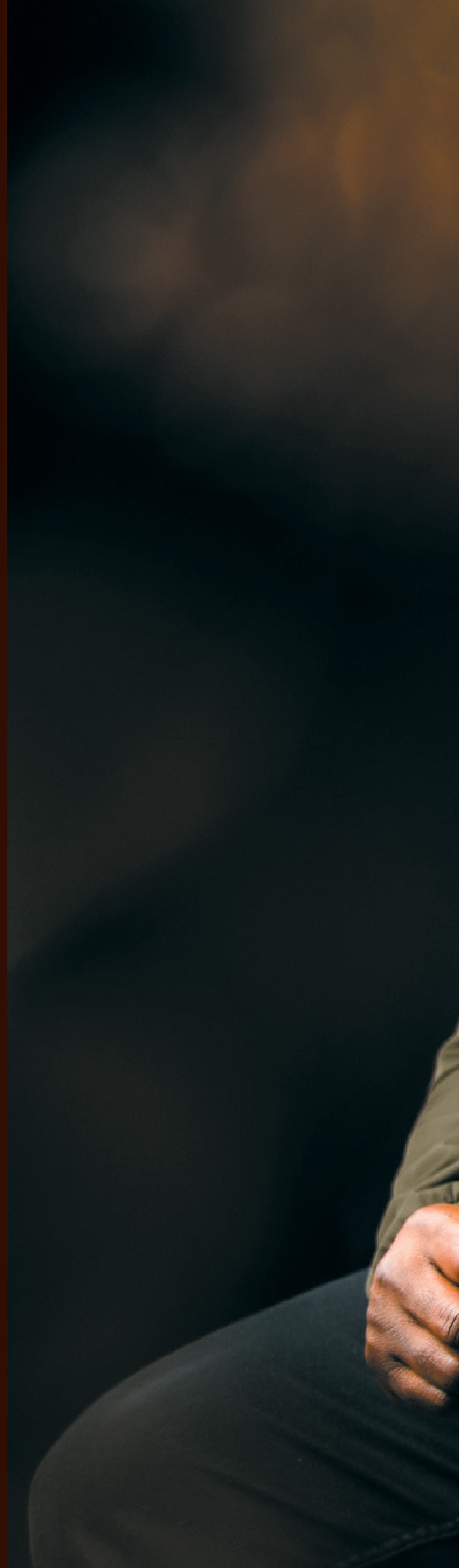
Clockwise from top left: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gills;
NASA/JPL-Caltech/SwRI/MSSS (*image data*), Gerald Eichstädt (*image processing*);
NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill; NASA/JPL-Caltech/SwRI/MSSS/Abastumani-63

Witch Hunts

Vicious attacks on women often accompany economic upheavals

By Silvia Federici and Alice Markham-Cantor

Photographs by Kholood Eid



A FAMILY MEMBER holds a portrait of Iquo Edet Eyo, who was killed in Nigeria in October 2022.

Silvia Federici is co-founder of the International Feminist Collective and professor emerita at Hofstra University. Her many books include *Caliban and the Witch* (2004) and *Re-Enchanting the World* (2019).

Alice Markham-Cantor is a writer and fact-checker based in Brooklyn, N.Y. Her book on witch hunts will be published by Llewellyn in 2024.

IT'S AN OLD STORY: A WOMAN IS ACCUSED OF WITCHCRAFT BY SOMEONE CLOSE TO HER—a neighbor, a relative, a rival. Often the original accuser resents or envies the woman or has a property dispute with her. At first the complaints are just whispers. But then something happens—a child gets sick, or an accident occurs. The woman's name is said again, loudly this time, and more people echo it. Then she is dragged from her house and killed.

This is what happened to Iquo Edet Eyo, a 69-year-old woman from Cross River State in Nigeria. Along with four others, she was murdered in October 2022, allegedly by a group of young men who charged that her witchcraft had caused a recent motorcycle crash. Her family says that suspicions had been dogging her for years, arising from jealousy of her prosperity. It is also the tale of Martha Carrier, the ancestor of one of us (Markham-Cantor), who was hanged in Salem, Mass., in 1692. Of the accusations against her, one of the most salient was by a neighbor with whom her family had a property dispute. Carrier became one of 35 people executed for witchcraft in the British colonies of New England—"crimes" of which some of them still have not been exonerated.

The narrative could be set in Germany in 1581, India in 2003, Uganda in 2018 or Papua New Guinea in 2021. Every year more than 1,000 people around the world, including men and children, are tortured, expelled from their homes or killed after being charged with witchcraft—using magic, usually to cause harm. Far from declining with modernization, as some 20th-century scholars predicted, witch hunts are holding steady in some places and may be happening more often in others.

Multiple roots entwine to produce a witch hunt. A belief in sorcery, a patriarchal society, sudden and mysterious deaths resulting from a paucity of health care, inaccessible justice systems that give impunity to attackers, a triggering disaster—all of these contribute. But as one of us (Federici) has argued in her 2004 book *Caliban and the Witch* and subsequent publications, what sustained periods of witch-hunting have in common, across time, space and culture, is a backdrop of social and economic dislocation.

Witch hunts can erupt suddenly, as during the COVID-19 pandemic, when terrified people searched for scapegoats. But when rates of these assaults have stayed high over decades—such as in Europe in the 16th and 17th centuries and in parts of Asia and Africa in the past 50 years—subsistence economies were in the process of being replaced by monetary and capitalistic systems.

During these times the powerful and the wealthy were privatizing fields, ponds and forests previously held as commons, evicting villagers from the natural resources that had sustained them for centuries. Close-knit communities with relatively self-sufficient economies disintegrated, leaving the newly dispossessed with wage work as the only option for survival. This disruption of rural society caused bitter conflicts between the emerging classes of haves and have-nots that in places manifested as witch hunts.

As Federici and other scholars have further argued,

in medieval Europe, as well as in much of the Global South, women harvested food and medicinal herbs and had a close relationship with the natural world. During expansions or intensifications of capitalism, many rural women lost access to land and, along with it, the economic and social power they had previously enjoyed. Among the worst affected were older women, who in the new dispensation were regarded as unproductive. Lacking social support and believed to have destructive magical powers, in many places they came to be targeted as witches. The pattern began six centuries ago with the witch hunts in Europe.

SILVER RIVER

IN THE MEDIEVAL PERIOD, Europe had a feudal system in which kings granted land to nobles, landlords and knights in exchange for military assistance in wartime. Despite often brutal exploitation, peasants could supplement whatever they earned from laboring on landlords' fields with food and other resources harvested, hunted or fished from commonly held fields, meadows, ponds and forests. Women enjoyed relative economic independence. Apart from tending crops, women worked as brewers, bakers, butchers, ironsmiths, retailers, and much more. Between 1300 and 1500 in Frankfurt, Germany, for example, women participated in more than 200 professions, with the municipality hiring at least 16 female doctors for its public health-care program.

With the conquest of the "New World" in the 16th century, however, silver from the mines of South and Central America began pouring into Europe—paradoxically deepening the immiseration of the poor. Inflation skyrocketed, and the purchasing power of wages collapsed, making even the most basic foodstuffs prohibitively expensive. The consequences were especially disastrous for women. They were primarily responsible for feeding and caring for their families but could not travel long distances to look for better-paying jobs. In the 14th century, for example, women received half the pay of a man for the same task; two centuries later they made only a third of the (reduced) male wage—and that money went to the husband.

Landlords and wealthier peasants had been fenc-

SILVIA FEDERICI (*left*) and Alice Markham-Cantor study witch hunts old and new.

ing off communally held fields, forests and meadows since the 13th century, and this process intensified. Rents escalated on whatever land was still available to the poor for farming. In the 1500s, writes historian E. B. Fryde, enclosure destroyed more than 2,000 rural communities in England alone. By the end of that century a full third of the English population had no access to land—and thus no ability to grow food necessary for survival.

Entire communities that had survived through cultivation in common fields found themselves facing mass impoverishment, with two main choices: emigrate or become wageworkers. Older women were particularly affected. Previously, in many feudal estates, a widow had rights to parts of her husband's holdings, as well as the right to glean crops from other fields. The breakdown of this "manorial" system left many of those women dependent on charity.

Caught between the collapse of wages and the loss of land, peasants rioted across Europe. In Germany, the aristocracy brutally suppressed a peasant rebellion between 1522 and 1525, murdering some 100,000 people. In most of these rebellions, men took the lead, but some of the protests against enclosures during the reign of King James I of England were made up only of women. In 1602, for instance, "Captain" Dorothy Dawson led 37 women in an attack on laborers who were fencing in a village commons in Yorkshire, England. Historian Yves-Marie Bercé similarly notes that in six out of the 31 food riots he studied in 17th-century France, all the protesters were women.

This is the economic ground on which the "Great Hunt" of witches in Europe took place. Although popular imagination regards the trials as outbreaks of mass delusion or superstition, the fact that they peaked between the 1580s and the 1630s, a time of massive upheaval as a capitalist economy emerged, suggests a different story.

Church leaders had initiated witch hunts in the late 15th century, in part as a way of policing social mores. Now the state, which was closely allied with religious, political and economic elites, took the lead. In the 16th century rulers across Europe introduced new laws to make sorcery punishable by death—and the trials moved from ecclesiastical to secular courts, such as in duchies and towns. Historian Christina Larner writes that in Scotland, authorities systematically incited panic against witches, traveling from village to village to instruct people on how to recognize them and sometimes even bringing along lists of women to denounce.

Many of those accused as witches were older women who no longer had a legitimate means of survival. As listed by historian Keith Thomas, the following were the crimes of 65-year-old Margaret Harkett, who was hanged at Tyburn, England, in 1585:

> She had picked a basket of peas in a neighbor's field without permission. Asked to return them, she flung them down in anger; since when, no peas would grow in the field. Later, William Goodwin's servants denied her yeast, whereupon his brewing-stand dried up. She was struck by a bailiff who had caught her taking wood from his master's ground; the bailiff went mad. A neighbor refused her a horse; all his horses died.

INTERFOTO/Alamy Stock Photo *(left)*; Bettmann/Getty Images *(right)*

WOMEN being persecuted as witches feature in many depictions of premodern Europe. A toad excavated from a woman's chest (*left*) "proves" that she was a witch, in a German print from about 1500. *The Duckingstool,* by Charles Stanley Reinhart, shows a woman being tortured by near drowning (*center*). In 16th-century Holland, a woman is about to be burned alive (*right*).

> Another paid her less for a pair of shoes than she asked; later he died. A gentleman told his servants to refuse her buttermilk; after which they were unable to make butter or cheese.

Not all alleged witches were poor and landless, however, and sometimes hunts served to dispossess them. Witch-hunting escalated when local edicts permitted officials or judges to seize the property of the accused. And it declined when the laws were modified to punish witchcraft without such confiscation. Witch finding could also be lucrative. Matthew Hopkins, England's most famous witch-hunter, reportedly made £1,000 over his career—almost $200,000 today.

Anyone who tried to save a witch, such as a "gossip," or a female friend, also risked being killed. Women had organized protests against enclosures with the help of other women, but conversations among them were now so stigmatized that "gossip" came to mean frivolous chatter or backbiting. To save their lives, gossips had to denounce their friends as witches.

Although the hunts targeted only some, the threat of being accused affected the behavior of most women. The persecutions contributed to the construction of a new patriarchal divide that degraded and limited women, ranking them below men. Over the course of the witch hunts, craftsmen in Germany pushed women out of guild membership, and even practicing certain trades, like selling goods in a market, put women at risk of sorcery accusations. In France, women lost the right to make their own contracts. And when they married, women and all that they owned effectively became the property of their husbands.

With a large population of laborers regarded as essential to prosperity, sexuality came to be rigorously policed. Those accused of witchcraft were often women who were believed to have sex outside of marriage or village healers and midwives, among whose many tasks was to provide contraceptives or abortifacients. As industrialization proceeded, many women were allowed back into the workforce in manufacturing centers and factories—but their husbands still received their wages.

In sum, witch-hunting was a systematic campaign of terror that eliminated the resistance to dispossession that had simmered for decades after the peasant protests were crushed. The accusations and persecution died down only in the latter half of the 18th century. Historical records indicate that by that time, roughly 50,000 people had been executed for sorcery.

IN THE COLONIES

THE DEMAND FOR SILVER and gold among Europe's elites also spurred witch hunts in South America, where repression helped to crush rebellions against colonization and round up laborers for the mines. In 1562 in Mexico's Yucatán Peninsula, Spanish authorities tortured some 4,500 people on the charge of worshipping idols, flogged them in public to terrify the populace, and enslaved the survivors in mines. When the Taki Onqoy movement in Peru sought to invoke the power of *huacas,* or deities, against Spanish rule, a Catholic council convened in 1567 decreed extirpation of "witch doctors," and a century of persecution followed.

As Indigenous people were being executed for devil worship in South and Central America, witch trials

Classic Image/Alamy Stock Photo

arrived in the North American colonies. When the elites of New England wrote Bible-inflected legal codes in the early 1600s, they included witchcraft as a crime punishable by death. The first official trial, in 1647 in Connecticut, was probably influenced by a wave of executions in England. By 1725 more than 300 people had been accused of witchcraft in New England, nearly four fifths of whom were women.

As in Europe, those persecuted as witches in the colonies were commonly poor and marginalized, but women who transgressed Puritan behavioral norms or who attained wealth or property were also at risk. Martha Carrier did both. She became pregnant out of wedlock, and after her immediate male relatives died in a smallpox outbreak, she may have stood to inherit much of her father's land. Carrier refused to confess, and in August 1692 she became one of the 19 people hanged for witchcraft in Salem.

Across the world, including in other colonies, witch hunts spiked for diverse local reasons but almost always in periods of social or economic upheaval. Tanvi Yadav of the Central University of Rajasthan writes that in 19th-century British India, when colonial authorities seized the land of upper-caste people, the sufferers blamed the loss on witchcraft by Dalit, or oppressed, women and started a campaign of witch-hunting against them. Unable to punch up, the recently dispossessed focused on the vulnerable target of the lower-caste witch.

MODERN WITCH HUNTS

LIKE THOSE IN PREMODERN EUROPE, many contemporary witch hunts can be traced to expansions or intensifications of capitalism. Across the Global South, governments and corporations have appropriated fields, forests and rivers for development projects such as highways, hydropower plants and mines, displacing between 90 million and 100 million people in the 1990s alone. The new wave of enclosures increased inequality; fragmented communities; worsened child and maternal health; and deepened social, gender and intergenerational conflicts. The economic decisions that enriched some people while impoverishing others were made in distant cities and, for the most part, in foreign languages, and few people could discern their origins.

In a detailed analysis of the Gusii region of Kenya, anthropologist Justus Ogembo, then at Harvard University, held international development policies responsible for an explosion of witch-hunting in the

ARTWORK in Federici's apartment includes *Reclaim the Commons* (*left*), by Erik Ruin; depictions of struggles, among them *Peasants Revolt*, by Rachel Hewitt, to the right (*center*); and a poster (*right*) on the International Wages for Housework campaign, which Federici co-founded in 1972.

1990s. To meet stringent conditions attached to an International Monetary Fund loan in 1981, Kenya slashed public spending on education and health care—just as the AIDS epidemic hit—and removed price controls on food and other necessities. Witchcraft accusations surged as people sought to assign blame for their suffering. Umar Habila Dadem Danfulani, a professor of religious studies at the University of Jos in Nigeria, similarly indicts the economic stresses induced by austerity policies, noting that at that time fear of witchcraft beset some ethnic groups with no prior history of it. The numbers of homeless children in cities rose, as did an increase in witchcraft accusations in the 1990s—especially of children.

Leo Igwe, founder of the Nigeria-based group Advocacy for Alleged Witches (AfAW), which assists victims of witch hunts, observes that when social welfare programs are cut, the accusations increase. The less the presence of the state in people's lives, he says, "the more of people scapegoating the disabled, scapegoating children, scapegoating the elderly, scapegoating women in trying to make sense of stressful economic situations."

Economic rivalry contributed to an outbreak of witch-hunting in the Democratic Republic of the Congo in 2003. Members of a faction competing for control of the Mongbwalu gold mines accused women who were ethnically linked with an opposing group first of spying, then of witchcraft. Human Rights Watch estimated that as many as 70 women and men were executed in the resulting witch hunts.

Historian and missionary Hugo Hinfelaar similarly notes that in Zambia in the 1990s, witchcraft allegations were "particularly rife in areas earmarked for game management and game ranching, for tourism, and for occupation by potential big landowners." Because of the paucity of reporting, just how many witch hunts derive from such competition over resources is unknown. As Hinfelaar writes, however, some chiefs and village headmen profit from selling land used by the community to international investors, "and fomenting social disruption in the villages facilitates such transactions." A village torn apart by sorcery allegations, he explains, "will not have the power to unite and oppose attempts to having the land they cultivate being taken over by someone else."

As fertile fields available to the marginalized become scarce, conflict over even a small plot can indirectly precipitate a "witch" killing. In cultures that fear sorcerers, says Miranda Forsyth, a researcher with Aus-

A FILING CABINET in Federici's home contains materials used for *Caliban and the Witch* (2004) and other books.

tralian National University's Sorcery Accusation Related Violence Project, "if you are in a land dispute already and a misfortune happens to you, then you're far more likely to think, 'It must have been those people who have caused this.'"

Around the world witch hunts have also been used to directly seize land. A 2021 report on attacks in Odisha, India, written jointly by a state government agency and the social justice organization ActionAid, found that a significant fraction of witch hunts involved explicit land grabs. In Kilifi, Kenya, where hundreds of men are accused of witchcraft every year, hunts often stem from a desire to liquidate an elderly man's land. Mzee Samuel Kazungu, chair of a group of men from 15 Giriama subtribes in Kenya who convene to address land disputes, told the outlet AllAfrica in 2021 that children "start demanding inheritance ... and since a father is not ready to release his property, his family will gang up against him and he will be branded a witch, killed and the land will be sold."

A close relative of Iquo Edet Eyo, who was murdered last October in Nigeria, attributes the accusations against her to jealousy: she owned land she cultivated, and she also got financial help from her daughter, who lived in the U.S. "When I was growing up, there were always accusations of witchcraft, but there wasn't anything like this," he says. "People didn't go and drag folks out in the square and beat them up and club them with the machete."

In Namibia, Berrie Holtzhausen, founder of Alzheimer's Dementia Namibia, a group that defends elderly people with dementia (which can be seen as signifying a witch) from accusations, notes that people who have become wealthy will often hide their assets when visiting rural family members. They arrive without their car, thinking, he says, that "if people see that I'm doing well now, they will believe that I somehow stole [through] magical powers." There is also a generational conflict at work, pitting young men who see no future except through the monetary economy against an elderly population for whom security is having land, trees or cows.

Professional witch finders make matters worse. In some places, they double as pastors who, influenced by evangelical and Pentecostal missionaries, encourage believers to attribute their daily misfortunes to the work of Satan. Some witch finders may genuinely believe that they are protecting communities from danger, but just like Hopkins in 17th-century England, many find the profession lucrative.

In Malawi, witch-hunters sometimes charge accused witches up to $100, Igwe says. If the victims cannot pay, the witch finders may seize their land or hold them hostage until their family members pay up. In Namibia, "for a witch doctor to make a ruling on whether or not you are a witch, you have to pay him a lot of money," Holtzhausen says. "To survive a witch-hunt accusation, you have to pay. The witch doctors are all rich people—and the witch doctors are almost all men."

THE RESISTANCE

IN RECENT YEARS students and others have campaigned for justice for the 17th-century victims of New England's witch hunts. Massachusetts has exonerated those who were charged of witchcraft there and issued a formal apology, but a similar effort in Connecticut this spring received unexpected pushback. "Do you have any evidence that this person was innocent?" State Representative Doug Dubitsky asked a descendant of one of the executed women—apparently suggesting that she could have been a witch after all.

Around the world women and organizations such as AfAW, Stop Sorcery Violence in Papua New Guinea and the women's leadership nonprofit Anandi in Gujarat, India, are fighting back against witch-hunting. In the summer of 2021, after six years of lobbying by a coalition of witch-hunt survivors, nongovernmental organizations, academics and lawyers, the United Nations passed a resolution condemning witch-hunting and ritual attacks.

Laws against witch-hunting, such as those passed in a number of Indian states, make it easier to prosecute people who accuse others of witchcraft. But Eyo's relative noted that in many places, poor people who are victims of witch hunts have little access to legal recourse. What may help reduce the persecutions, as in South Africa, is providing pensions to the elderly, which appears to confer social protection.

One of the most potent responses to modern-day witch hunts is the struggle to hold back, and even reverse, the process of land dispossession and wealth concentration that began centuries ago during Europe's Great Hunt. In Brazil, women from a number of Indigenous groups have led an effort to defend the Amazon forest and waters from extractive industries. In Bolivia, they have marched repeatedly to prevent the construction of highways—which bring loggers, ranchers, settlers and oil drillers—through Indigenous lands. In Kenya, they have planted millions of trees as part of the Greenbelt Movement, an effort for which Wangari Maathai, its founder, won the Nobel Peace Prize in 2004. In India, they are engaged in numerous struggles against logging and mining. And in the U.S., Native American women played leading roles in the Standing Rock movement to safeguard water from contamination by an oil pipeline.

These initiatives are not only oppositional but also constructive. Even as they confront polluters and developers, women are involved in restoring forests, rediscovering forms of agriculture that support rather than destroy other creatures, and rebuilding a web of community relationships that represents the best form of defense against violence. SA

FROM OUR ARCHIVES

Dialogues with the Dead. Piers Vitbesky; January 2023.

scientificamerican.com/magazine/sa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COMMONS

BIOENGINEERING

Designing Life

Synthetic morphology is enabling scientists to coax living matter into shapes and forms never seen in nature

By Philip Ball

Illustration by Richard Borge

Philip Ball is a science writer and former *Nature* editor based in London. His next book, *How Life Works* (University of Chicago Press), will be published in the fall of 2023.

IN THE COLLECTION OF THE PEABODY MUSEUM AT HARVARD UNIVERSITY RESIDE THE MUMMIFIED remains of a very peculiar creature. It has the shrunken head, torso and arms of a monkey, but from the waist down, it is a fish. This bizarre hybrid was bought by Moses Kimball, founder of the Boston Museum, from the family of a sea captain. Kimball leased it in 1842 to the impresario P. T. Barnum for his popular American Museum in New York City. Barnum claimed it was a mermaid found in Fiji.

In fact, such artifacts, typically intended for sale, were made from animal parts by fishermen and artisans in Japan at the time (although some of the mermaid seems to be fashioned from papier-mâché). Mythical hybrid beasts such as mermaids, centaurs and chimeras testify to our enduring fascination with the plasticity of biological form: the idea that natural organisms can mutate or be reconfigured. Both in legends and in fiction, from H. G. Wells's 1896 novel *The Island of Doctor Moreau* to the 2009 movie *Splice,* we seem inclined to imagine living organisms as assemblies of parts that can be shuffled and rearranged at will.

But a crude stitching of components will not produce a viable organism. Bodies aren't a collection of arbitrary pieces; a human embryo grows into a being with the standard features of a human body, all the parts working in synchrony. Biological forms seem to have inevitable, unique target structures.

An emerging discipline called synthetic morphology is now questioning that notion. It asks how, and how far, the natural shapes and compositions of living matter can be altered. The goal is not to create grotesque creatures such as the Fiji Mermaid but to understand more about the rules of natural morphogenesis (the development of biological form) and to make useful structures and devices by engineering living tissue for applications in medicine, robotics, and beyond.

Synthetic morphology might be considered the next stage of synthetic biology. The latter discipline has racked up impressive achievements in retooling cells for nonnatural tasks—for example, programming bacteria to glow in the presence of pollutants and other chemicals. Much of synthetic biology involves genetic engineering to introduce networks of genes that give cells new functions, such as manufacturing enzymes to make a nonnatural molecule.

Synthetic morphology works at the next level: controlling the shapes and forms into which many cells will assemble. Using the cells of multicellular organisms (like us), the technology might allow scientists to design entirely new tissues, organs, bodies and even organisms by exploiting the tremendous versatility and plasticity of form and function that seem to reside in living matter. The possibilities are limited only by our imagination, says bioengineer Roger D. Kamm of the Massachusetts Institute of Technology. We might design a novel organ, for instance, that secretes a particular biomolecule to treat a disease, similar to the way the pancreas secretes insulin. It could have sensor cells that monitor markers of the disease in the bloodstream, akin to controlled-release implants already used to administer drugs—but alive. Or, Kamm says, we could make "superorgans" such as eyes able to register ultraviolet light outside the visible spectrum.

Ultimately we can imagine creating entirely new living beings—ones shaped not by evolution but by our own designs. "By studying natural organisms, we are just exploring a tiny corner of the option space of all possible beings," says biologist Michael Levin of Tufts University. "Now we have the opportunity to really explore this space." Synthetic morphology poses deep questions that challenge the status quo in biology: Where does form come from? What rules has evolution developed for controlling it? And what happens when we bypass them? Doing so could turn on their heads our traditional notions of body, self and species—even of life itself.

THE RULES OF LIVING FORM

THINKING OF LIVING MATTER as a substance that can be shaped and engineered at will was a revolutionary idea that arose in the 19th century. Zoologists had long regarded biological forms as innate, and Charles Darwin argued that natural selection sculpts them to be adapted to their environment. In the mid-1800s others, such as Darwin's supporter Thomas Henry Huxley, began to suspect that there was a generic form of "living matter"—often called protoplasm—from which the most primitive life-forms were fashioned.

In his 1912 book *The Mechanistic Conception of Life,* German physiologist Jacques Loeb argued that life could and should be understood according to engineering principles. After discovering that he could stimulate asexual reproduction by treating unfertilized sea urchin eggs with simple salt solutions, he became convinced that nature's way of doing things with living matter is not the only way. "The idea is now hovering before me," he wrote, "that man himself can act as a creator, even in living nature, forming it eventually according to his will."

Around the same time Loeb's book was published, French physician Alexis Carrel developed techniques for growing tissues in a culture medium: a kind of unformed living material. He hoped it might become possible not just to preserve but to grow organs outside the body for transplantation when the natural ones wear out, thereby conveying the prospect of immortality.

That hasn't happened, but tissue culture is now a well-established technology used to make, for instance, synthetic skin for grafts. It is now routine to cultivate living cells, including those of human tissues, in a petri dish, sustaining them with the nutrients they need to metabolize, replicate and thrive—much as we can grow colonies of bacteria or yeast.

The idea of cells as the "building blocks" of our bodies might make them seem rather passive, like mere bricks to be stacked in the masonry of tissues. But they are much smarter than that. Each cell is in many respects a living entity in its own right, able to reproduce, make decisions, and respond and adapt to its environment. Multicellular living matter concocts its own schemes, which means cells won't necessarily stay in the same place or state.

This is strikingly apparent in the development of a new organism—a human being, say—from a single fertilized egg, or zygote. As that single cell becomes two, four and eventually many billions, it changes from what looks like an unstructured ball of identical cells to a body with a well-defined shape containing distinct tissues in which cells carry out different roles—producing the electrically coordinated contractions of the heart, for example, or secreting the hormone insulin in the pancreas.

Scientists and natural philosophers have wondered for millennia where this body plan comes from. How does the featureless blob that is the early embryo know what to make and where to make it? The answer, according to biology textbooks, is that the plan is contained in the cells' DNA, encoded by genes. But this notion quickly falls apart. Yes, all the zygote seems to get by way of instruction is a genome, but you will look there in vain for any blueprint for a heart or brain. The genes simply encode proteins or other molecules that can ramp their production up or down.

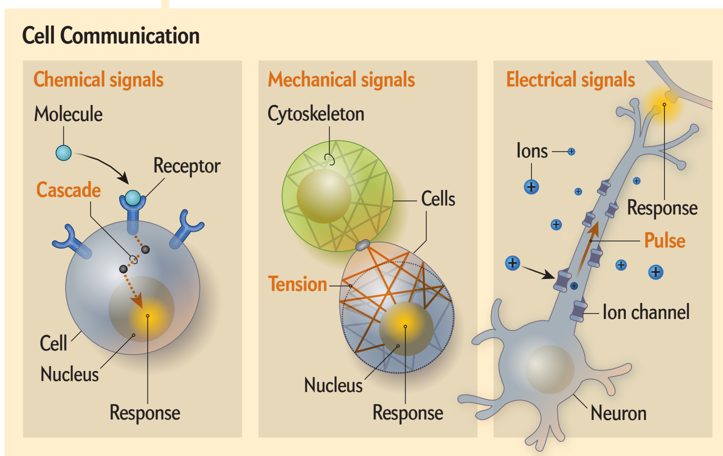
It's better to think of the molecular networks of the cell as encoding certain behaviors and tendencies, from which morphology emerges when those impulses play out among many cells. To understand—and perhaps ultimately to control—the forms of multicellular structures, we need to figure out these behavioral rules.

Cells produce order and form by communicating with and responding to one another. Each is bounded by a membrane studded with molecules, generally proteins. These molecules are capable of receiving signals at the cell surface and converting them into messages within the cell's internal networks, typically ending with the activation or suppression of specific genes.

There are three main modes of communication for these externally derived signals. One is chemical: a molecule arrives at the cell surface and binds to a protein receptor there, triggering some change in the receptor that initiates a signaling cascade in the cell's interior.

Alternatively, activity within a cell can be altered by mechanical signals such as stretching of the membrane when another cell sticks to and pulls it. Typically these mechanical signals are "transduced"—converted to some internal effect—by membrane proteins that alter their behavior when pulled or squeezed, to admit or exclude, for instance, electrically charged ions attempting to enter the cell.

The third mode is directly electrical. Ions passing across a cell's membrane can make the cell electrically polarized. That's how electrical signals are transmitted through heart muscle to induce regular contractions: the pulses travel from cell to cell via connections called gap junctions. Such electrical signaling is a capability shared by most cells.



Levin thinks bioelectric signaling between cells creates particularly powerful information-processing capabilities that can influence morphology. It therefore represents a useful "control knob" for applications in regenerative medicine and synthetic morphology, he says. Levin, Vaibhav Pai of Tufts and their colleagues have shown that the development of neural structures in the frog brain seems to be governed by the voltage across the membranes of embryonic cells. When the researchers permanently activated a key gene called *Notch* (one of the factors that induces precursor cells to become neurons in frog embryos), brain development was disrupted. But they were able to put it back on the right track by changing the membrane voltage of other cells nearby: the bioelectrical signal overrode

Graphics by Jen Christiansen

the message coming from the genes, allowing proper morphogenesis to proceed.

Morphogenesis is a subtle process involving the interplay of information at the scales of the whole organism, the genetic and molecular activity in its cells, and everything in between—a complex mixture of bottom-up, top-down and middle-out signaling. If cells multiply faster in one part of the embryo than another, the developing tissue may buckle and fold. This deformation creates mechanical stresses that feed back into those cells to switch certain genes on and off, differentiating the cells from others around them and directing them along a developmental trajectory toward a particular tissue or organ.

In another example, as a mass of cells grows in a fetus, those in the interior might get cut off from the oxygen-ferrying blood pulsing down capillaries, triggering them to produce and release chemicals that induce some of their neighbors to develop into blood-vessel-forming cells. There was never any blueprint for a vascular system in the cells' DNA; rather the eventual network of branching tubes is an emergent morphology produced by the rules of cell interaction and response.

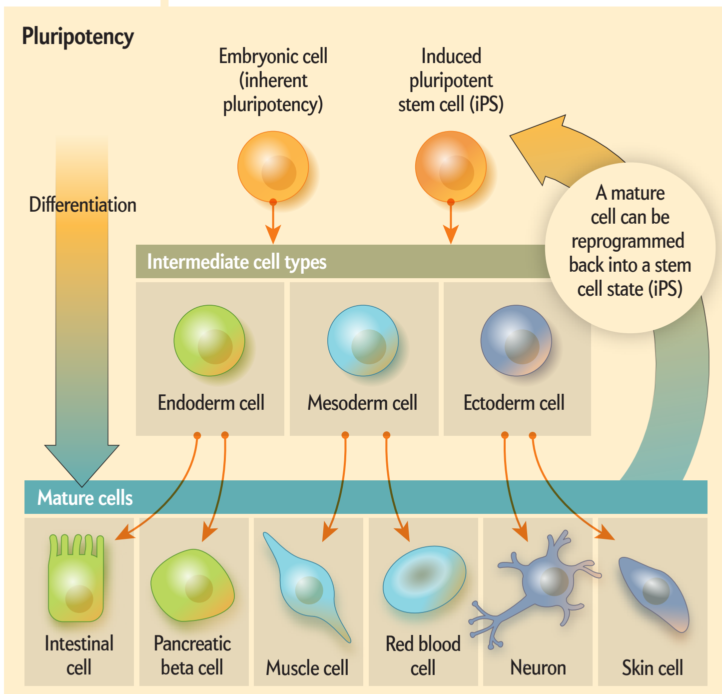
"The genome specifies a cellular collective with massive plasticity," Levin says, "which executes rearrangements until the correct target morphology is achieved." One of the most striking illustrations of the existence of such target forms is the way a tube called the pronephric duct, a precursor to the kidney, grows in newts. If cells had genetic instructions telling them to assemble into a tube, we would expect bigger cells to make a proportionately bigger tube. In the 1940s, however, embryologist Gerhard Fankhauser tested this idea by using cells with extra chromosomes that made them grow larger than their usual size. He found that a tube of normal diameter and thickness developed—it just contained fewer cells. The largest cells changed shape to make the structure almost on their own. It was as if the cells collectively "knew" what their target structure was and adjusted their individual behavior accordingly. Albert Einstein was fascinated by these experiments, writing to Fankhauser that "what the real determinant of form and organization is seems quite obscure."

An even more striking example of this apparent "overall vision" of multicellular structures is found in primitive flatworms called planarians. Cut a chunk out of a planarian, and it will regrow exactly those tissues that were removed, neither more nor less. Even a small part of a planarian can regenerate into a full worm with the typical shape and proportions. This capacity is all too evidently lacking in humans—so how do planarians do it? It seems to entail an ability of the regenerating cells to "read" the overall body plan: to take a peek at the whole, ask what's missing and adapt accordingly to preserve morphological integrity. They are able to make use of top-down information. Levin believes this information is delivered to the cells via bioelectric signaling, which governs the maintenance of form in other organisms such as fish, frogs and humans. When he and his colleagues manipulated pieces of planarians to alter their bioelectric state, the regenerating cells produced unexpected anatomies—for example, worms with a head at each end.

Such regenerative potential is available to amphibians such as axolotls and salamanders, which can regrow limbs and tails that have been amputated. That feat demands two morphological capacities: the regrowing cells must be able to develop into many tissue types, such as skin, muscle, bone and blood vessel, and those tissues have to spontaneously organize themselves in the right way. Amphibians keep a reserve of such versatile cells, called stem cells, for repair jobs. If we are to find ways of imbuing our own bodies with regenerative powers, we need to know and master the global rules governing form.

THE PLASTICITY OF CELLS

All embryos contain a ball of cells that are able to develop into any of the body's tissue types, a property called pluripotency. In humans, however, these cells gradually lose this plasticity through a succession of transformations that differentiate them into specialized roles. It was long assumed that when these embryonic cells lose their pluripotency, that versatility is gone forever. But in 2006 biologist Shinya Yamanaka of the University of California, San Francisco, and his co-workers showed that this isn't so. They were able to switch mature, differentiated mammalian cells back into a stem-cell-like state by injecting them with a cocktail of the genes that are active in embryonic stem cells (ESCs), essentially rewinding the clock of embryo development. Their experiment demonstrates that the fates of our cells, and the nature of our tissues and bodies, are far less inevitable and inexorable than people had thought: living matter is plastic and programmable.



Cell reprogramming is now being explored for regenerative medicine. Some researchers are seeking to combat macular degeneration, a common cause of blindness, by reprogramming cells in the eye to support light-sensitive retinal cells. Others hope to cure neurodegenerative diseases such as Parkinson's or spinal injuries by using neurons made from induced pluripotent stem cells (iPSCs) that can restore damaged connections in the nerve networks.

When cells are reprogrammed, they also acquire new morphological knowhow. For example, skin cells reprogrammed into iPSCs that are then cultured as neurons in a petri dish might not simply grow into a tangled mass. In the right growth medium, they might instead try to become a brain, recapitulating some of the structures seen in developing brains, with organized layers of cortexlike neurons and some of the characteristic folds seen in a mature cortex.

Such reprogrammed cells are not terribly good at making whole organs because they are missing some important information that, in an embryo, would come from the surrounding tissues. And currently such "organoids" can't grow very large because they lack a vascular network, meaning the cells in the center eventually become starved of nutrients. To solve that problem, researchers are looking for ways to encourage some of the cells to develop into blood vessels. If transplanted into mice, liver organoids will spontaneously integrate with the animal's own blood supply.

Another demonstration of the versatility of cells in multicellular structures is provided by so-called chimeric embryos, which contain cells from more than one type of organism. Because very different species usually can't interbreed, monstrous hybrids such as the Chimera of Greek mythology seemed biologically implausible; the only way to make something like the Fiji Mermaid was to crudely stitch together lifeless carcasses. But at the level of individual cells, the species barrier isn't as important as we might think. All cells speak much the same language, and those of different species seem to get along fairly well in an embryo. Scientists have created several chimeric animals—mosaics of cells of different species, such as the goat-sheep blend called a geep—by adding stem cells from one species to the embryo of another.

The further the evolutionary distance, the more precarious the chimera becomes. Some researchers are now experimenting to see whether "human" organs, made from human stem cells (either ESCs or iPSCs), can be grown in livestock animals such as pigs and cows to create a reservoir of organs for transplantation.

All this testifies to the fact that there is nothing fixed or inevitable about biological morphology at the level of cells. If that seems surprising, it is perhaps because we have been so wedded to the blueprint picture of developmental biology. But that picture demands excessive—in fact impossible—overspecification of the body plan. A blueprint could never, for example, dictate how every one of our 86 billion neurons should be wired up.

All evolution needed to do was specify basic rules of cell communication and behavior that, when played out in the known, predictable environment of the womb or egg, would reliably create a specific morphology.

Perhaps that is the most efficient way to make complex organisms: not to program every cell to go to a particular place and become a specific thing in a paint-by-numbers fashion, but rather to give cells rules of interaction that enable them to figure the rest out for themselves. Change the environment, though, and those same rules might produce a very different end result. That was startlingly illustrated in recent work by Levin, Douglas Blackiston of Tufts and their colleagues. They simply broke up frog embryos into small pieces and left them to do what they would in a nutrient medium. "If we give them the opportunity to reenvision multicellularity," Levin says, then "what is it that they will build?"

Over a couple of days the cells clumped into little clusters that began behaving like multicellular microorganisms, sprouting cilia, hairlike protrusions that beat in a synchronized way to propel the clusters through the fluid. These structures, which the researchers called xenobots (in reference to the Latin name of the original organism, the African clawed frog *Xenopus laevis*), will re-form their shape if damaged, suggesting that there is some kind of "goal" to their morphology. It was as if the genetic instructions in these cells, combined with the laws of cell interaction they support, could give rise to a completely different kind of organism than the frogs that would develop in normal circumstances. "We have the opportunity to make creatures in 48 hours that have never existed before," Levin says. Now he is imagining making organisms that are reconfigurable and "immortal" in that "when they die, the individual cells crawl off and make their life alone and maybe rejoin again later into something else."

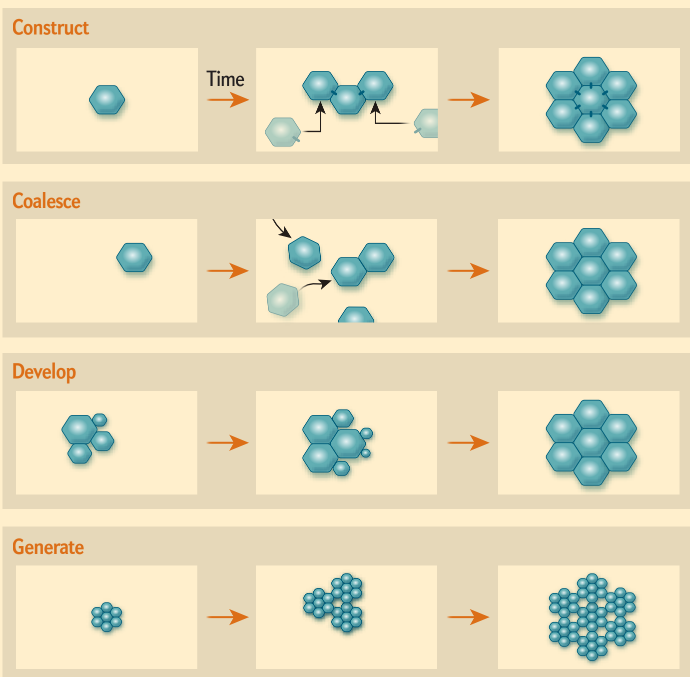
MORPHOLOGICAL ENGINEERING

ORGANOIDS, chimeras and xenobots all suggest that cells can make stable entities other than those Darwinian evolution supplies. We can select and generate target morphologies by design. "We can definitely force cells to create shapes that are not natural," says cell biologist Marta Shahbazi Alonso of the University of Cambridge. Working out the rules governing synthetic morphology, however, is a much harder task than figuring out how to build with blocks that have specific assembly rules, such as LEGO bricks.

With cells, the blocks are themselves changed by the assembly process. "In a simple mechanical world, you would have pieces that interact with each other following a set of rules to build more complex structures," Shahbazi Alonso says. But, she adds, the "beauty of development"—and also the complication—is that "the process of building a structure changes the very nature of the building blocks. Throughout development there is constant cross talk from processes that happen at different scales of biological organization."

Synthetic morphology, then, demands a new view of engineering in which we assemble objects from their basic components not in a simple assembly-line manner according to a blueprint. We must exploit rules of interaction to enable a desired structure to emerge as if by collective agreement of the parts—by recognizing that those parts themselves have a kind of agency. Computational biologist René Doursat of the Complex Systems Institute in Paris identifies four categories of processes involved in such morphological engineering: Agents can attach to one another in a programmed construction or assemble via swarmlike coalescing. Alternatively, a structure may develop via growth and multiplication of the components, or it can generate itself by repeating an algorithm, like that which produces the fractal forms of plants.

Synthetic Morphology Engineering Approaches



The challenge, Doursat says, is to find ways of ensuring reliable outcomes that will not be thwarted by small perturbations and that are adaptive—if circumstances change, the system needs to be able to find a solution that does the job. This philosophy has much in common with the way we create cities and societies: We have some idea of what we would like, but we can't control it from the bottom up. We can only try to guide the self-organization along the right lines.

Doursat and his colleagues have proposed theoretical schemes for building with bacteria in this way, using synthetic genetic circuits to imbue them with interaction rules that will produce simple geometric elements made of many cells, such as rods and rings. Those shapes might then be assembled into higher-order structures. Some of the earliest work on multicellular synthetic biology also used bacteria. For example, Frances H. Arnold of Caltech, Ron Weiss of M.I.T. and their co-workers engineered a population of bacteria with genetic circuitry that allowed each cell to sense the population density in its environment and control the rate of spontaneous cell death, keeping the population growth within specified limits.

Kamm and Weiss, together with tissue engineer Linda G. Griffith, also at M.I.T., recently launched a multidisciplinary Center for Multi-Cellular Engineered Living Systems at the university, which builds on such work to create multicellular systems with specific functions by design. They believe that making these living systems will require a range of approaches, including everything from top-down patterning (where the cells are inserted into position "by hand") to bottom-up self-organization (where the cells are programmed to self-assemble into a target structure).

Suppose you need to replace an artery and want to make a simple flow valve consisting of a blood-vessel-like tube of cells that is encircled at one point by a ring of muscle cells able to contract. You could make these two shapes out of a synthetic scaffold, such as a biodegradable polymer, and seed them with the two cell types, which would colonize the relevant components. That's the top-down approach. Or you could start with a cluster of stem cells that can be tweaked and guided to differentiate in the right way while they move and coordinate with one another, eventually producing that same structure—that's bottom-up, and more like the way the body builds such structures. The first approach may be simpler and could involve tools such as bioprinting, in which cells are delivered to specified locations by an ink-jet-style device. But it might be harder to keep the resulting structure stable. What if different types of cells want to fuse or develop into other tissues? The bottom-up approach, in contrast, would build on stem cells' ability to sustain themselves and make repairs if damaged.

Kamm says we don't yet have good methods for reliably generating and predicting such outcomes. But they're coming. One useful tool is optogenetics, which is already used to study the neural basis of behavior by switching specific neurons on and off. In this approach, scientists use genetic engineering to direct cells to make light-operated protein switches that control their electrical state. Fine laser beams can then be used to activate specific cells in a group and send them along particular developmental trajectories. Kamm says it might also be possible to selectively activate and differentiate cells mechanically (by poking them in various locations or using light-based optical tweezers to pull on them), thermally and bioelectrically (by, say, changing their membrane potentials at certain locations).

BUILDING NEW LIFE

WHAT SHOULD WE BUILD with such tools? One goal is to create living multicellular structures that resemble but don't exactly mirror natural ones: a simplified, idealized tissue or organism, for instance, that helps to elucidate the processes that go on in the natural, more complex variety. Several researchers are assembling human stem cells into embryolike structures ("embryoids") so they can watch the very early stages of embryogenesis in vitro.

If grown outside the uterus, the embryo cells don't receive essential signals from their environment that would help orient and guide their development. They may begin to differentiate into the more specialized types that would eventually become part of tissues such as skin, blood and nerves—but it happens in a rather random, unstructured way. In 2014, however, Ali H. Brivanlou of the Rockefeller University and his co-workers showed that merely confining human ESCs within small circular "sticky" patches is enough to instill some order.

Brivanlou and other researchers are finding ways to make embryoids ever more like the real thing. Magdalena Żernicka-Goetz of the University of Cambridge and her colleagues have demonstrated that if they mix mouse ESCs with two other embryonic cell types (trophoblast stem cells and extraembryonic endoderm stem cells), they will organize themselves into a kind of hollow structure like a peanut shell that resembles the central amniotic cavity of real embryos. The cells seem to "know," roughly, what an embryo looks like, and they not only organize themselves accordingly but also begin to differentiate into the correct specialized tissues.

It's not clear how far these embryoids might be grown in vitro—but Żernicka-Goetz and others have made embryoids that will develop to the stage where limbs and organs start to form. If an embryoid were to be implanted in a womb—a procedure that would clearly be unethical in humans but might be contemplated in other animals—who knows what it might go on to do?

That's not a rhetorical question. We can't take it for granted that a synthetic embryoid will somehow find its way onto the usual track of embryo growth. It might pursue a different path entirely. That's one reason for the lack of consensus on the ethical management of these entities. Should they be subject to the same rules and regulation that govern research with human embryos? Or are they a different thing entirely, one made of human cells on a different developmental path?

Robotic engineers are using living tissues as components in otherwise conventional robots. They generate behaviors that would be tricky to engineer with purely artificial materials and devices. Kit Parker of Harvard's Wyss Institute for Biologically Inspired Engineering has collaborated with aeronautical engineer John Dabiri of Caltech and bioengineer Janna Nawroth of the Helmholtz Pioneer Campus in Germany to make a "medusoid," a creature that looks like a jellyfish robot. It uses rat muscle tissue attached to a silicone polymer to produce undulating contractions, which allow it to swim like a real jellyfish. Parker and his colleagues also used rat heart muscle cells in a robot that swims by means of rippling motions modeled on those of the ray fish. By using optogenetics to control the activity of the muscle cells, the researchers were able to regulate the speed and turning motion of the robot so it could be guided by light through an obstacle course.

Chemical biologist Adam Cohen of Harvard and his co-workers, meanwhile, have made an "engineered bioelectric tissue" that can generate electrical oscillations. The electrically active cells in their structures were human embryonic kidney cells they engineered to produce ion-channel proteins, which let ions flow in or out to regulate the potential of the cell membrane. In some of the cells, the researchers used genetic engineering to add genes encoding other ion channels, enabling optogenetic switching with red and blue light. By combining these cell types in a ring, they made a light-activated structure that generated waves of electrical activity moving around the ring. The waves could be made to travel in either direction, meaning these structures could be used to encode binary information. Perhaps we could ultimately process data in a kind of living computer.

Synthetic morphology demands a new view of engineering, one in which we exploit rules of interaction to enable a desired structure to emerge.

Understanding the rules that govern biological morphology might open up new possibilities for entirely artificial technologies such as robotics. James Sharpe of the European Molecular Biology Laboratory Barcelona and Sabine Hauert of the University of Bristol in England have programmed coin-sized cylindrical robots to self-assemble in swarms using principles that mimic those of living cells, communicating via short-range infrared signals. The swarms show a pseudobiological ability to form robust collective shapes that can adapt to damage and self-repair: a kind of inorganic, robotic tissue.

Levin thinks all this is just the start for synthetic morphology. "My conjecture is that cell collectives are universal constructors," he says. Given a particular set of living components, we can make them do anything that is acceptable within the laws of physics.

But to do that, we'll need a new mindset for engineering—one appropriate for dealing with materials that are not merely "smart" in the traditional sense of responding to their environment but that have genuine agency. This collaboration between engineers and their materials might entail letting go of some of our conventional categories for distinguishing machines, robots and organisms. Synthetic morphology implies that life can be remade if we relax the boundaries separating the natural from the artificial. SA

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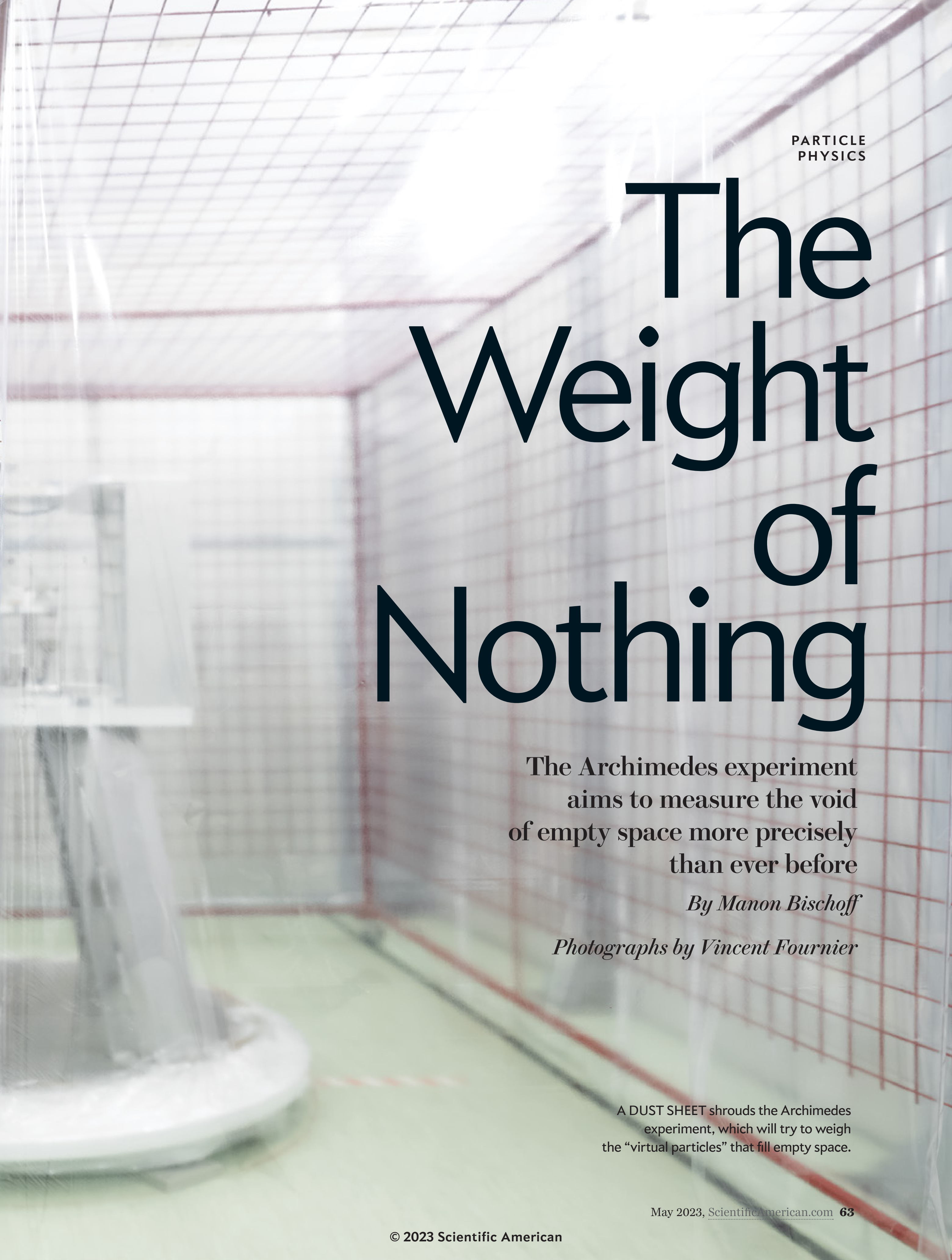


PARTICLE PHYSICS

The Weight of Nothing

The Archimedes experiment aims to measure the void of empty space more precisely than ever before

By Manon Bischoff

Photographs by Vincent Fournier

A DUST SHEET shrouds the Archimedes experiment, which will try to weigh the "virtual particles" that fill empty space.

Manon Bischoff is a theoretical physicist and editor at *Spektrum,* a partner publication of *Scientific American.*

IT DOES SOMETHING TO YOU WHEN YOU DRIVE IN HERE FOR THE FIRST TIME,” ENRICO CALLONI SAYS as our car bumps down into the tunnel of a mine on the Italian island of Sardinia. After the intense heat aboveground, the contrast is stark. Within seconds, damp, cool air enters the car as it makes its way into the depths. “I hope you’re not claustrophobic.” This narrow tunnel, which leads us in almost complete darkness to a depth of 110 meters underground, isn’t for everyone. But it’s the ideal site for the project we are about to see—the Archimedes experiment, named after a phenomenon first described by the ancient Greek scientist, which aims to weigh “nothing.”

The car stops, and our driver, Luca Loddo, gets out and equips everyone with helmets and flashlights. We cover the last part of the trip on foot, deeper and deeper into the tunnel. We pass a door to a room where seismographs record the subtle movements of the surrounding earth. Finally, a cave appears on the left side of the tunnel, with a spotlight pointing at it, and we stop. “This is where it’s supposed to take place,” explains Calloni, a physicist at the Italian National Institute of Nuclear Physics.

Geologically, Sardinia is one of the quietest places in Europe. The island, along with its neighbor Corsica, is located on a particularly secure block of Earth’s crust that is among the most stable areas of the Mediterranean, with very few earthquakes in its entire recorded history and only one (offshore) event that ever reached the relatively mild category of magnitude 5. Physicists chose this geologically uneventful place because the Archimedes experiment requires extreme isolation from the outside environment. It involves a high-precision experimental setup designed to investigate the worst theoretical prediction in the history of physics—the amount of energy in the empty space that fills the universe.

Researchers can calculate the energy of the vacuum in two ways. From a cosmological perspective, they can use Albert Einstein’s equations of general relativity to calculate how much energy is needed to explain the fact that the universe is expanding at an accelerated rate. They can also work from the bottom up, using quantum field theory to predict the value based on the masses of all the “virtual particles” that can briefly arise and then disappear in “empty” space (more on this later). These two methods produce numbers that differ by more than 120 orders of magnitude (1 followed by 120 zeros). It’s an embarrassingly absurd discrepancy that has important implications for our understanding of the expansion of the universe—and even its ultimate fate. To figure out where the error lies, scientists are hauling a two-meter-tall cylindrical vacuum chamber and other equipment down into an old Sardinian mine where they will attempt to create their own vacuum and weigh the nothing inside.

WHAT’S IN EMPTY SPACE?

A VACUUM is not completely empty. This is because of an idea in quantum physics called Heisenberg’s uncertainty principle. The principle states that you can’t determine the position and the velocity of a particle at the same time with any precision—the more precisely you know one value, the less precisely you can know the other. This principle also applies to other measurements, such as those involving energy and time. Its consequences are considerable. It means that nature can “borrow” energy for extremely short amounts of time. These changes in energy, known as vacuum fluctuations, often take the form of virtual particles, which can appear out of nowhere and disappear again immediately.

Vacuum fluctuations have to respect some rules. A single electrical charge, for example, cannot suddenly appear where there

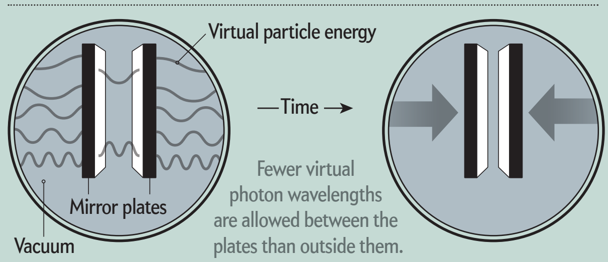
Map by Jo Hannah Asetre

PHYSICIST ENRICO CALLONI leads a team aiming to measure a minute signal with a complex and sensitive beam balance.

was none (this would violate the law of charge conservation). This means that only electrically neutral particles such as photons can pop out of the vacuum by themselves. Electrically charged particles have to emerge paired with their antiparticle matches. An electron, for instance, can appear along with a positron, which is positively charged; the two charges cancel each other out to preserve the total charge of zero. The result is that the vacuum is continuously filled with a stream of short-lived particles buzzing around.

Even if we can't capture these virtual particles in detectors, their presence is measurable. One example is the Casimir effect, predicted by Dutch physicist Hendrik Casimir in 1948. According to his calculations, two opposing metal plates should attract each other in a vacuum, even without taking into account the slight gravitational pull they exert on each other. The reason? Virtual particles. The presence of the plates imposes certain limits on which virtual particles can emerge from the vacuum. For example, photons (particles of light) with certain energies can't appear between the plates. That's because the metal plates act like mirrors that reflect the photons back and forth. Photons with certain wavelengths will end up with wave troughs overlapping wave crests, effectively canceling themselves out. Other wavelengths will be amplified if two wave peaks overlap. The result is that certain energies are preferred, and others are suppressed as if those photons were never there. This means that only virtual particles with certain energy values can exist between the plates. Outside them, however, any virtual particles can emerge.

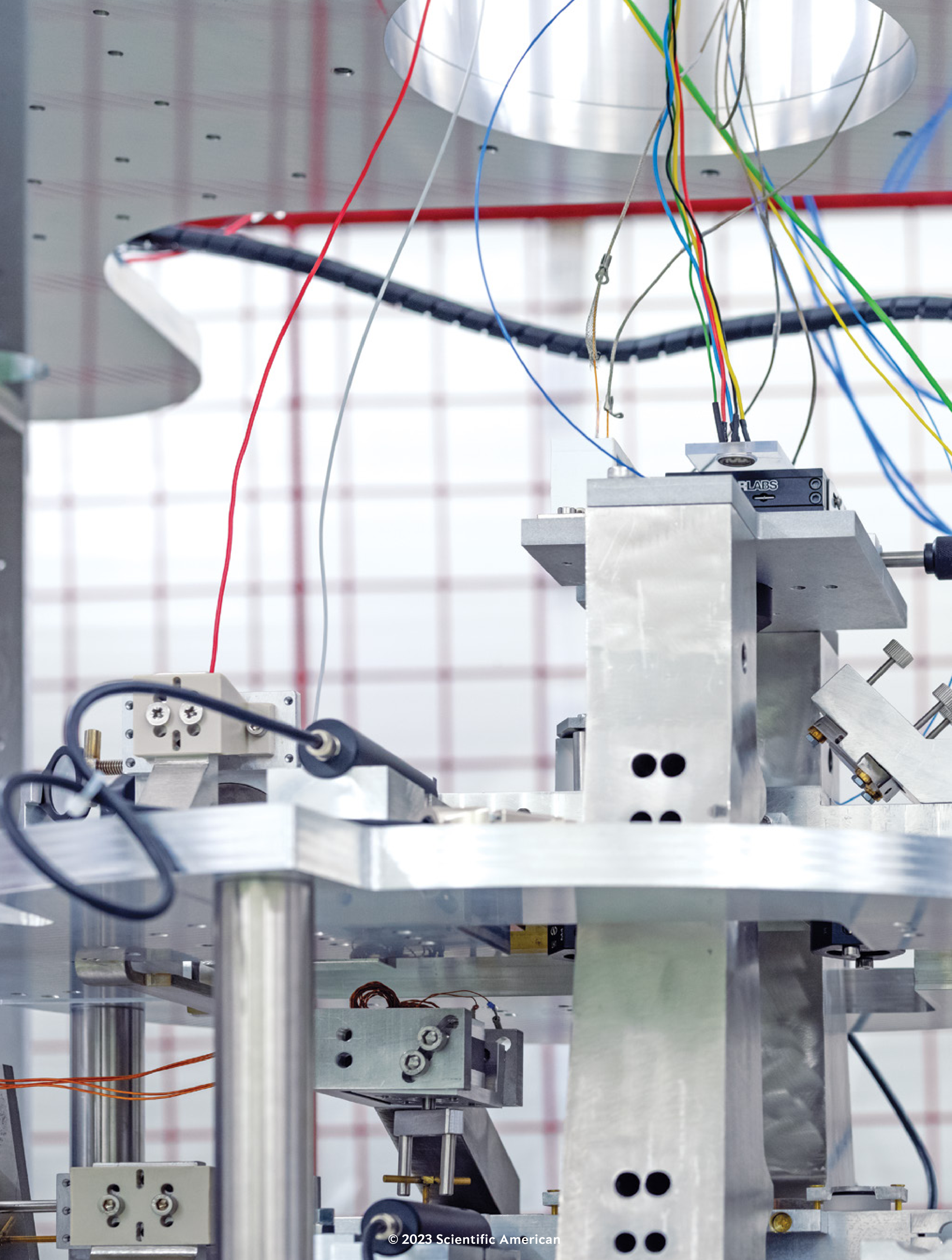
Casimir Effect



The result is that there are fewer possibilities—and therefore fewer virtual particles—between the plates than around them. The comparative abundance of particles on the outside exerts pressure on the plates, pressing them together. This effect, strange as it may sound, is measurable. Physicist Steven Lamoreaux confirmed the phenomenon experimentally at the University of Washington in 1997, almost 50 years after Casimir's prediction. Now Calloni and his colleagues hope to use the Casimir effect to measure the energy of the void.

This energy has important consequences for the universe as a whole. General relativity tells us that energy (for example, in the form of mass) curves spacetime. That means virtual particles,

Graphics by Jen Christiansen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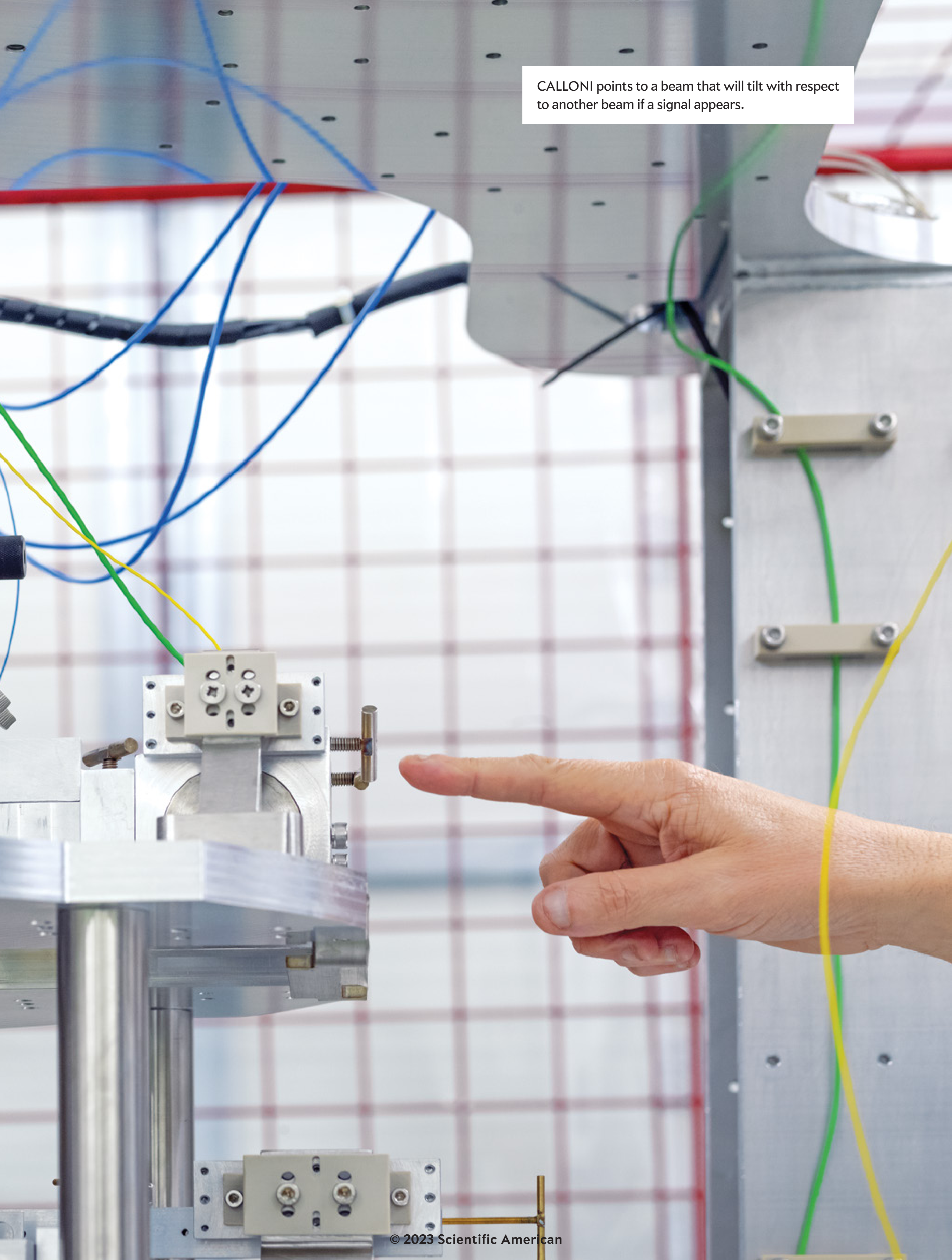
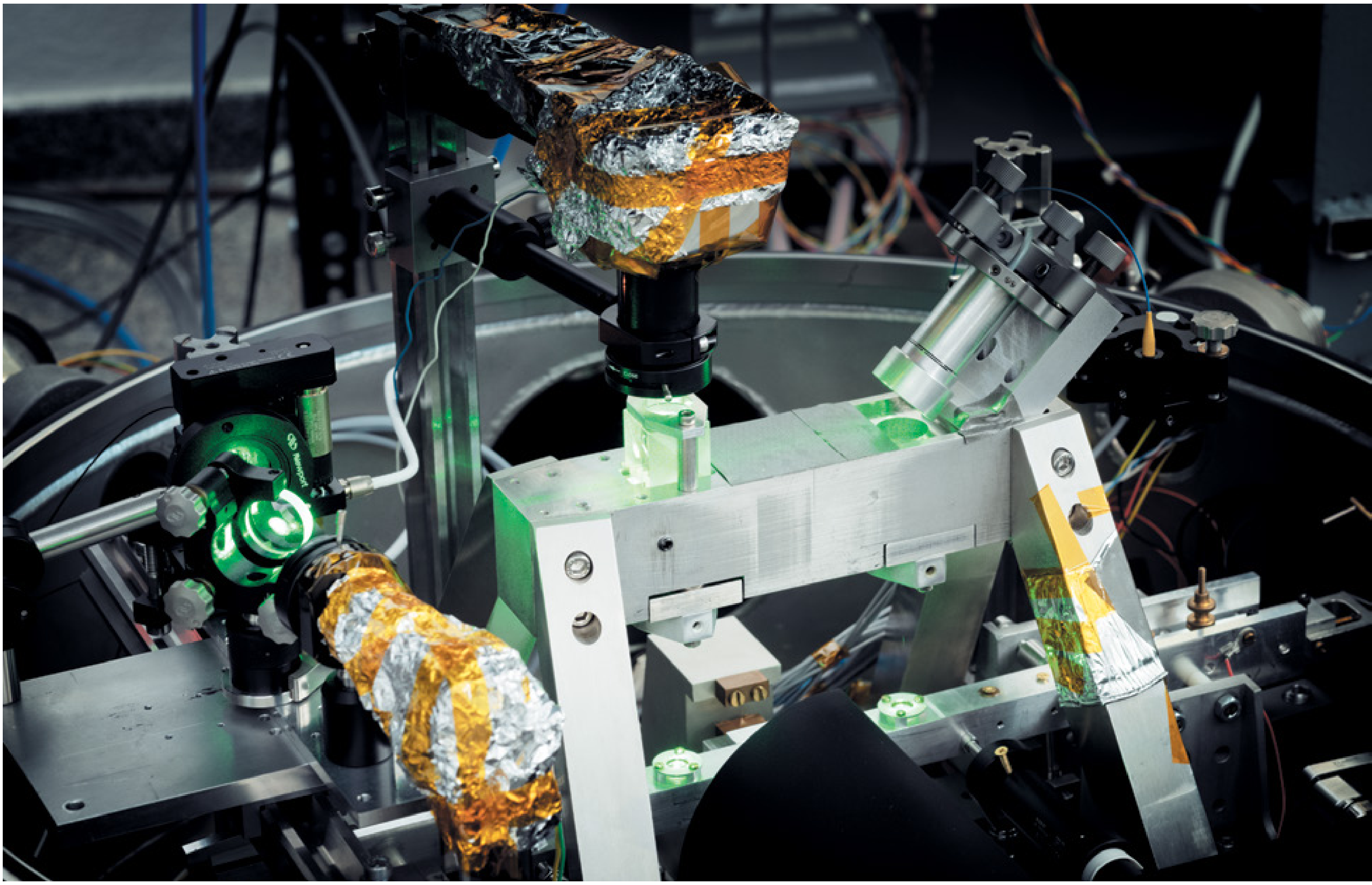


CALLONI points to a beam that will tilt with respect to another beam if a signal appears.



AN INTERFEROMETER will use lasers to measure any slight displacement in the beam balance.

which change the energy of the vacuum for a short time, have an effect on the shape and the development of our universe. When this connection first became clear, cosmologists hoped it would solve a major puzzle in their field: the value of the cosmological constant, another way of describing the energy in empty space.

THE COSMOLOGICAL CONSTANT

EINSTEIN PUBLISHED his general theory of relativity in 1915, but he soon realized he had a problem. The theory seemed to predict an expanding universe, yet astronomers at the time believed that our cosmos was static: that space had a fixed, unchanging size.

Three years after he published the theory, Einstein found that he could add a term called the cosmological constant to his equations without changing the fundamental laws of physics. Given the right value, this term would ensure that the universe neither expands nor contracts. In the 1920s, however, astronomer Edwin Hubble used the largest telescope of the time, the Hooker telescope at Mount Wilson Observatory in California, to observe that the farther away a galaxy was from Earth, the faster it seemed to be receding. This trend revealed that space was, in fact, expanding. Einstein discarded the cosmological constant, calling it "folly."

More than half a century later there was another twist: By observing distant supernovae, two research teams independently proved that the universe isn't just expanding—it's doing so at an accelerated rate. The force that pushes space apart has since been called dark energy. It acts as a kind of counterpart to gravity, preventing all massive objects from eventually collapsing into one place. According to theoretical predictions, dark energy accounts for about 68 percent of the total energy in space. At this point, the cosmological constant came back into fashion as a possible explanation for this mysterious form of energy. And the cosmological constant, in turn, is thought to get its energy from the vacuum.

At first, the scientific community was delighted: it seemed that general relativity's constant was the result of the energy of virtual particles in empty space. Two different fields of physics—relativity and quantum theory—were coming together to explain the accelerated expansion of the universe. But the joy didn't last long. When scientists did the two calculations, the energy of the vacuum based on quantum field theory turned out to be much larger—120 orders of magnitude higher—than the value of the cosmological constant astronomers derived from measuring the universe's expansion. The best way to resolve the discrepancy would be to measure the energy present in the vacuum directly—by weighing virtual particles.

A SCALE FOR THE UNIVERSE

IF THE VACUUM ENERGY derived from quantum theory is correct, then something must be stifling this energy's effects on the expansion of space. If this value were the true strength of dark energy, space would be ballooning much, much faster. If, on the other hand, the value from cosmology is right, then physicists are vastly overestimating how much energy virtual particles contribute to the vacuum.

That vacuum fluctuations and virtual particles exist has been widely accepted at least since the Casimir effect was demonstrated. And quantum theory's predicted strength for the fluctuations can't be completely off, either, because laboratory experiments confirm the theory to great precision. But might it be possible that virtual particles don't actually gravitate the way we think and therefore don't affect the weight of space as we tend to expect?

So far no direct measurements have ever been made of how virtual particles behave with respect to gravity. And some scientists have suggested they may interact with gravity differently than ordinary matter does. For instance, in 1996 physicists Alexander Kaganovich and Eduardo Guendelman of Ben-Gurion University in Israel worked out a theoretical model in which the fluctuations of the vacuum have no gravitational effect. This might be the case if there are extra dimensions beyond the regular three of space and one of time that we're familiar with. These hidden dimensions might modify the behavior of gravity on very small scales.

Yet mass differences in atomic nuclei of elements such as aluminum and platinum can be explained only if certain quantum fluctuations contribute to their weight. That's why many physicists are convinced virtual particles interact with gravity just as ordinary particles do. "There are clear indications of this but so far no direct proof," says theoretical physicist Carlo Rovelli, who was involved in the Archimedes experiment's theoretical planning.

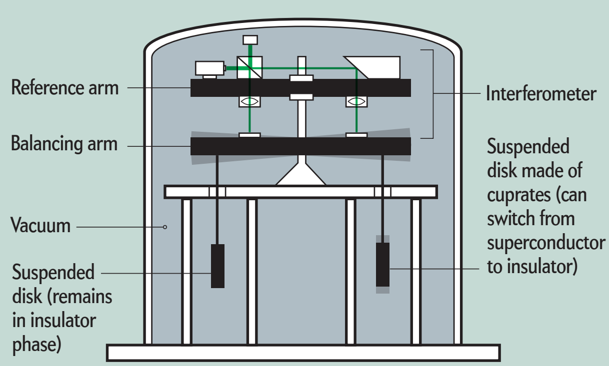
To verify that virtual particles interact with gravity like normal matter, the Archimedes team members want to use the Casimir effect to weigh virtual particles with a simple beam balance. The balance will sit inside their vacuum chamber, a cylindrical container of "nothing" that will be nested in several layers of insulation to keep it extremely cold and protected from the outside environment. Those layers, in turn, will sit deep inside the Sardinian cave, protecting the delicate apparatus from every possible influence of the aboveground world. These barriers are necessary because the scientists are searching for a minute signal: the slight movement of the balance when the Casimir effect turns on, changing the weight of a sample material by altering the population of virtual particles inside it. "In principle, we have known the basic principles needed for this for decades," explains postdoctoral researcher Luciano Errico, a member of the experiment team. "I wondered myself at first why it took so long to tackle this task."

In 1929 physicist Richard Tolman wondered if certain forms of energy (he focused on heat) could be weighed. Seven decades later Calloni thought about pushing the idea forward. After reading a technical paper by the late physicist Steven Weinberg, he envisioned weighing the gravitational contribution of virtual particles using Archimedes' principle, which states that when a body is immersed in fluid, it experiences an upward buoyant force equal to the weight of the fluid that the body displaces. If virtual particles have weight, then a cavity of metal plates in a vacuum should experience a buoyant force. The cavity is essentially displacing the regular vacuum, with its abundant virtual particles, with a lighter vacuum containing fewer virtual particles. Determining the strength of the buoyant force, which depends on the density of the virtual particles, will reveal their weight.

To measure this force within their vacuum tube, the researchers will suspend two samples made of different materials from a two-meter-tall, 1.50-meter-wide balance and induce the Casimir effect within one. To do this, they will heat both materials at regular intervals by about four degrees Celsius and then cool them down again. This temperature difference is sufficient for one of the samples to switch back and forth between a superconducting phase (when electricity flows freely within the material) and an insulating phase (when electricity cannot easily flow). The other material, however, always remains an insulator. As the conductivity changes in the first sample, it acts like the classic two-plate setup, and the number of possible virtual particles within it varies. Thus, the buoyancy force periodically increases and decreases on the first weight. This variation should cause the balance to oscillate at regular intervals, like a seesaw with two children sitting on it.

In planning the experiment, the scientists needed to find a suitable material that could be heated and cooled uniformly and quickly and that exhibited a strong Casimir effect. After considering several options, the team chose superconducting crystals called cuprates. The resulting samples are disks with a diameter of about 10 centimeters that are only several millimeters thick. To date, no one has proved that the Casimir effect works in high-temperature superconductors, but the scientists are betting that it does.

Archimedes Scheme



The researchers have rigged the balance so that it hangs freely in space within its vacuum chamber, which will cool the entire apparatus to less than 90 kelvins (just under –180 degrees Celsius). The chamber itself will be packed into two larger metal containers—one canister filled with liquid nitrogen, within another airless container, which acts like a thermos. Without that final cocoon, the second layer would heat up too quickly. The entire structure will be about three meters high, wide and deep and will weigh several tons.

A SENSITIVE SIGNAL

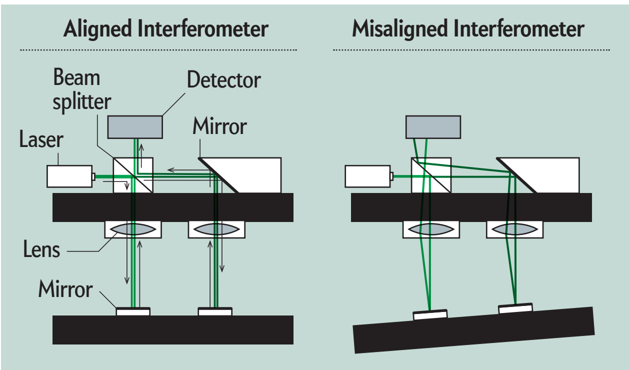
CALLONI BEGAN WORKING with colleagues in 2002 to develop a theoretical model to calculate the strength of the buoyancy force for different experimental setups. They found the force in a realistic experiment would be about 10^{-16} newton. Measuring such a tiny force is like trying to weigh the DNA in a cell. "The numbers are devastating," says physicist Ulf Leonhardt of the Weizmann Institute of Science in Rehovot, Israel. "On the other hand, 10 years ago hardly anyone believed gravitational waves could now be detected."

In fact, the technology in today's gravitational-wave detectors, which first observed their target in 2015, could help detect the tiny gravitational signals the Archimedes experiment seeks. Calloni himself was involved in building the Italian gravitational-wave detector VIRGO. "It is only because of the extremely sensi-

THE EXPERIMENT will eventually be housed in an abandoned Sardinian mine.

tive instruments made for precision measurements of gravitational waves that all this is possible," Errico says.

To be able to detect the minuscule deflections it seeks, the Archimedes experiment will use two laser systems that share some similarities with the laser-and-mirrors setups within gravitational-wave detectors. The first splits a laser beam in two by directing it through a beam splitter to both ends of the scale, where they are reflected by attached mirrors. The beams are then recombined by further mirrors and travel to a detector. If the beam is in balance, the two beams will travel exactly the same distance. If the arm is slightly tilted in one direction, the beams will cover different distances. In that case, the crests and troughs of the laser beam waves will meet in the measuring device in a staggered manner, producing a different intensity. This system can detect even the smallest deviations from equilibrium.



A second set of lasers measures the direction of the tilt if there is a large movement. A simplified prototype of the experiment that operates at room temperature is already remarkably sensitive, boding well for the final Archimedes apparatus's performance. But even with such sophisticated measurement systems, implementing the experiment will be difficult. "In experiments like this, the whole world works against you," says physicist Vivishek Sudhir of the Massachusetts Institute of Technology.

To shield the balance from the outside world, the physicists needed a site with as little seismic activity as possible—hence Sardinia. The island has other advantages. It's not too densely populated, which keeps human-made noise low. It also has more than 250 abandoned mines, many of them no longer in use, which are appealing because there are even fewer vibrations underground and because the temperature inside a mine is especially stable.

Eventually the team fixed on the Sos Enattos mine on the east side of the island, which has been closed since the 1990s. The mine has a long history: in ancient times, the Romans used it to extract silver and zinc ores. Today Loddo, our driver for the trip, is responsible for the shafts; he had previously worked as a technician in the mine. "Just before it was closed, there were only about 30 people working there," Loddo says as he walks us through the mine. "They then took care of converting the underground passages so that they could be used as a museum." A few years later he took over the mine's management and organized guided tours. In some areas, there are still educational installations depicting the different steps miners took in their work: here a figure filling a cart with rocks, there someone attaching explosives to a wall, and elsewhere an elaborate replica of a worker operating a pneumatic drill. "Today the mine is used only for scientific operations," Loddo explains.

The room where they plan to do the experiment looks more like an archaeological site than a laboratory, with its high walls of unadorned stone and vaulted cave ceiling. "The whole room has already been enlarged quite a bit, but there is still a lot of work to be done," Calloni says. The room still has to get bigger, for example. It needs a ventilation shaft, a proper floor, and more.

The final version of the balance setup was recently completed and shipped to Sardinia. The vacuum chamber is at the test site, but its two outer envelopes are still in production. When they arrive and when the cave is ready, scientists will move the entire setup to this dark underground room and start running real trials.

It's been a long process to get to this point. "It took me about six months to plan the setup in detail," Errico says. "Where should which adjusting screw go? What does the ideal beam splitter look like, and where do you position it? It then took about a year for all the parts to arrive and for me to put it together." And the calibration to get the laser to hit all the fixtures accurately? "That actually only took 30 minutes. I had planned everything so precisely that there were only a few degrees of freedom. When everything really worked out the way I had imagined, I almost cried with joy."

PRECISION MEASUREMENTS

DESPITE THE TEAM'S careful planning, the measurement will be quite challenging, says Lamoreaux, who first demonstrated the Casimir effect. "I have long dreamed of measuring the Casimir force between superconducting plates," he says. "But making a suitable sample was beyond my capabilities."

The experiment's precision measurements would have to be a factor of 10 better than the best gravitational-wave detectors operating today, points out Karsten Danzmann, director of the Max Planck Institute for Gravitational Physics in Hannover, Germany. He finds the project fascinating but ambitious.

If it works, though, the results will have major consequences. "The experiment is extremely important," Leonhardt says, "because it would prove that vacuum fluctuations are indeed a real quantity with a gravitational contribution." If the measurements match expectations and show that virtual particles interact gravitationally just like ordinary matter, then we will know for sure that vacuum fluctuations must affect Einstein's general relativity equations. Consequently, they probably have very strong effects. In that case, cosmologists will have to explain what suppresses the influence of vacuum energy in the universe.

If the deflections of the balance turn out differently than expected, it might mean several things. On the one hand, such a result could open the door to entirely new physics if it showed that virtual particles don't gravitate. But "a missing signal could also be because there is no Casimir effect in cuprates, or it is very weak," says experimental physicist Markus Aspelmeyer of the University of Vienna. "Therefore, it is even more important to test separately from this experimentally."

The Archimedes researchers themselves aren't making any predictions. "We don't want to formulate a hypothesis yet, so as not to falsify the experiment," Calloni says. "But whatever result we get, it will definitely be exciting." SA

FROM OUR ARCHIVES

Cosmic Conundrum. Clara Moskowitz; February 2021.

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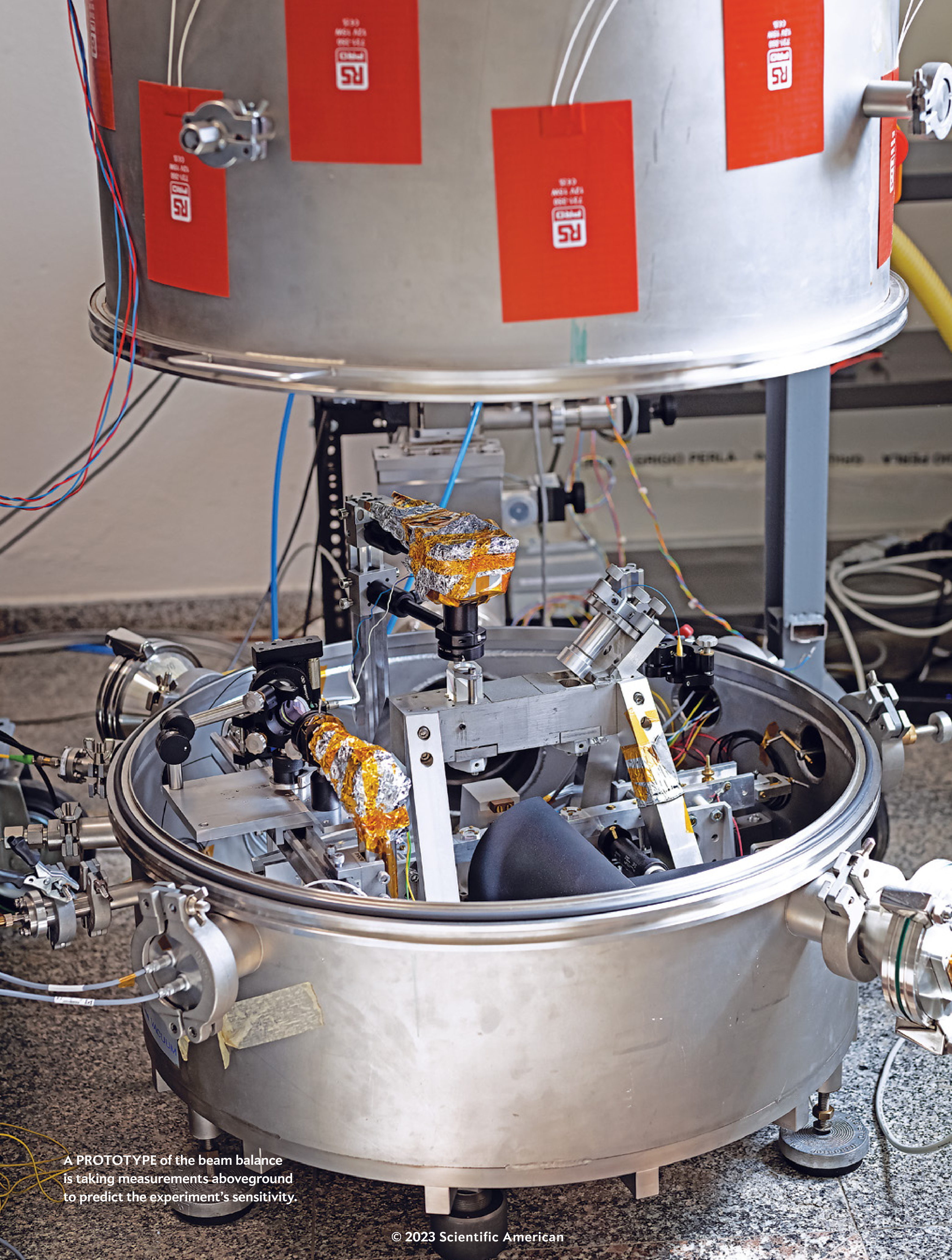


A PROTOTYPE of the beam balance is taking measurements aboveground to predict the experiment’s sensitivity.

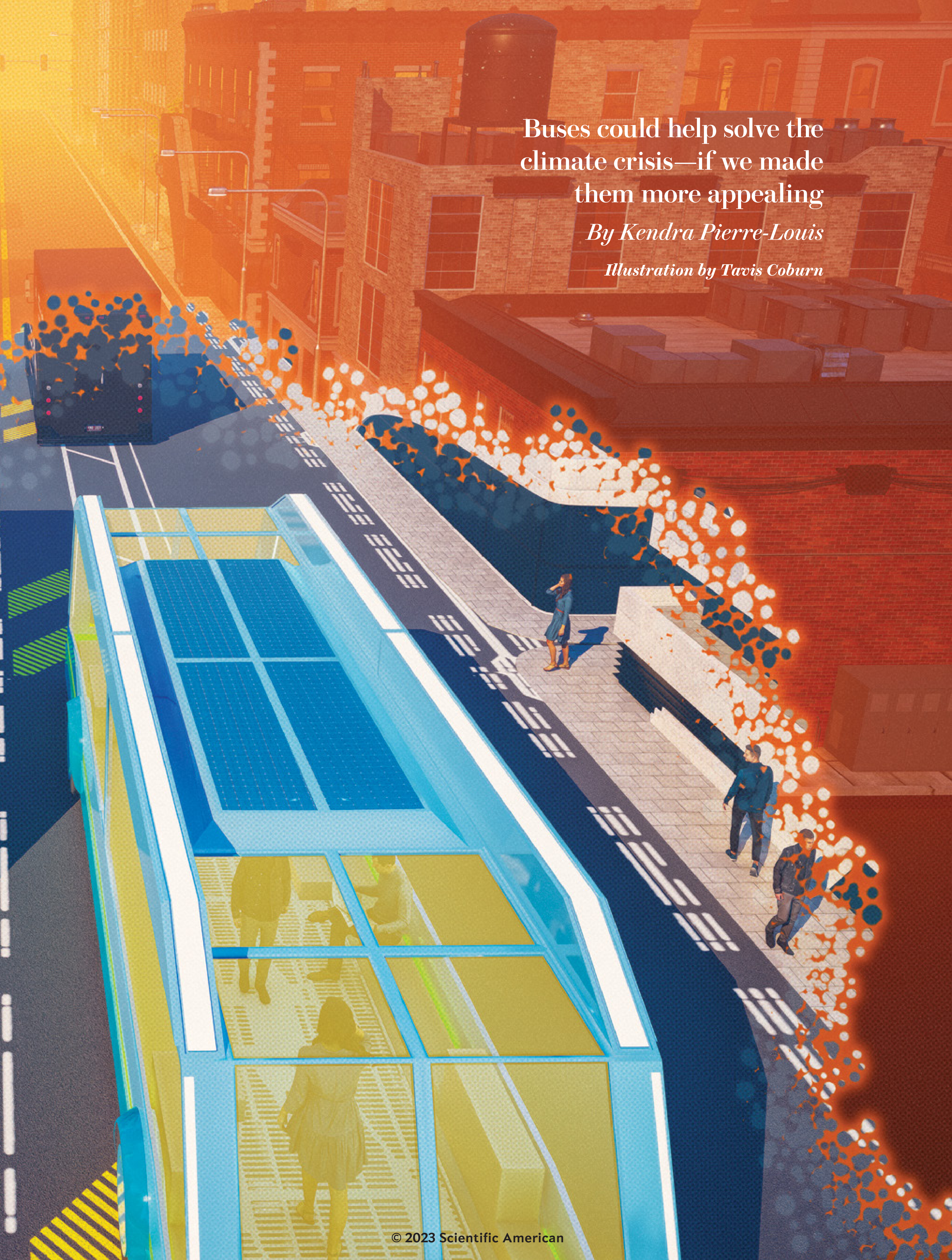
SUSTAINABILITY

Let's Take the Bus

Buses could help solve the climate crisis—if we made them more appealing

By Kendra Pierre-Louis

Illustration by Tavis Coburn



Kendra Pierre-Louis is a climate reporter focusing on the science and social impacts of climate change. She has worked for *Gimlet,* the *New York Times* and *Popular Science.* Pierre-Louis is based in New York City.

FOR THE PAST DECADE SEATTLE HAS BEEN GROWING—FAST. BETWEEN 2010 and 2020 its population swelled by almost a quarter. Growth is generally good for cities, but it is often accompanied by a dreaded problem: traffic. Yet Seattle managed to avert this crisis, cutting traffic in its downtown by 10 percent and reducing greenhouse gas emissions in the process. How did Seattle do it? By turning to an uncommon solution: the humble bus.

Buses are among the most overlooked solutions for decarbonizing the U.S. Transportation is the single largest source of greenhouse gas emissions, making up slightly less than 30 percent, according to the Environmental Protection Agency. In the summer of 2022 more than 5 percent of new auto sales in the U.S. were for all-electric vehicles (EVs), signaling that electric-car ownership had shifted from being a fad of early adopters to a transportation staple. Three of the four car commercials that aired during this year's Super Bowl were for EVs. In January, President Joe Biden tweeted, "On my watch, the great American road trip is going to be fully electrified," alongside a photograph of himself behind the wheel of an electric Hummer.

The president has supported EVs as part of the nation's climate plan, pledging to reduce emissions by 50 to 52 percent by 2030. This commitment is in line with the aims of the Paris Agreement. But Steven Higashide, director of the Clean Transportation program at the Union of Concerned Scientists, cautions that "electrifying personal vehicles is necessary but not sufficient" for achieving the nation's goals on climate change reduction.

A growing body of research bolsters his point. A 2018 report by the California Air Resources Board found that the state could not meet its 2030 climate goals through vehicle electrification alone. At the time, California aimed to reduce greenhouse gas emissions to 40 percent of the state's 1990 levels by 2030. But according to the report, even if there were 10 times as many EVs on the road, people would still need to reduce their driving by 25 percent for California to reach its target.

The culprit is something known as vehicle fleet turnover—that is, how long it takes to shift the mix of vehicles that are on the road. Even if every new vehicle sold from now on were electric and directly replaced a gas-powered car, it would still be at least 15 years before virtually every car on the road was electric. But sales of new gas cars are still higher than those of EVs, which is why even the more ambitious estimates say roughly a third of cars will still be gas in 2050.

Even if the U.S. could somehow avoid the fleet-turnover problem, swapping gas cars one-for-one with EVs would create new energy needs requiring half of the country's electricity-generating capacity, according to a 2020 analysis in the journal *Nature Climate Change.* This demand would limit the nation's ability to power other things such as air-conditioning that are necessary for health and safety in a warming world. To meet the country's climate goals, Higashide says we'll have to drive less frequently and for shorter distances—and redesign cities and neighborhoods with good mass transit options.

Buses can fill a lot of those needs. It's better if they're powered by electric batteries, but even gas busses reduce emissions with enough riders. On aver-

AN UNSAFE BUS stop in Staten Island, N.Y.: poorly located, lit and maintained, with no sidewalks or crosswalks.

age, cars emit almost one pound of carbon dioxide per passenger mile. Buses, which generally run at about 25 percent capacity, emit 0.64 pound of CO_2 per passenger mile, according to data from the Department of Defense. If they ran full, buses would emit 0.18 pound of CO_2 per passenger mile, making them comparable to rail but at a much lower cost. "I think the bus is often overlooked as a climate solution," Higashide says, "because it is overlooked as a solution, period."

CONVERTING DRIVERS TO RIDERS

BUSES HAVE LONG been maligned in popular imagination. In movies and television shows, scriptwriters often have characters ride the bus to telegraph to viewers that they are facing tough times. On the HBO series *Insecure,* main character Issa Dee's downward spiral begins with her crashing her car and having to ride the bus. In the ultimate bus flick, *Speed,* Annie is on the bus because her driver's license has been revoked—for speeding. Why else would a nice girl like her be riding the bus in Los Angeles?

It would seem that buses are a hard sell in a country that loves the automobile, but research suggests that isn't necessarily true. According to a 2016 analysis led by Higashide that looked at transit-ridership behavior among both car owners and those without cars, people who live near better transit ride it more often regardless of whether they own a vehicle. The problem is that many Americans do not live near better transit. An analysis by the American Society of Civil Engineers found that 45 percent of people in the U.S. lack access to transit at all. Those who do have transit available find it is often slow and unreliable.

The amount of time between buses or trains at a given stop, known as headway, has a huge impact on whether people will actually use the service. "Ten minutes is that magic mark," says Kari Watkins, an associate professor of civil and environmental engineering at the University of California, Davis. Watkins's research looks at how to expand mobility through methods other than driving. When a bus arrives every 10 minutes or less, riders don't have to think about when the bus is coming. This experience mirrors the main convenience of private car ownership: transportation is available when you need it.

When buses arrive every 15 or 20 minutes, "people are still going to feel like they have to time their trips," Watkins says. Past that, "anybody who has a choice is not as likely to opt for transit." Buses that

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AN ELECTRIC BUS in Zaragoza, Spain (*left*). In Bogotá, Colombia, the TransMilenio system (*right*) has dedicated bus lanes that run to the airport.

Marcos Cebrian/Europa Press/Getty Images

arrive with an unpredictable cadence because of traffic and other factors also turn people away.

In this way, trains have some benefits over buses because they run on a fixed schedule. The two modes are probably best used in a complementary way: rail can carry large numbers of people in denser communities, and buses can serve to funnel people to those rail lines. Even in New York City—a place well known for its subway system—buses shuttle more than one million riders daily. Buses are also much nimbler than trains because they leverage an existing piece of infrastructure: the road. Routes can be adjusted to meet shifting needs, whereas train tracks cannot be moved.

Yet "in many parts of the country, there has been an investment in rail without the corresponding investment in bus service," Higashide says. He points to Denver: the city has spent billions expanding its light rail and commuter rail systems, but "then you get off the train, and the bus comes every hour."

David King, a planning professor at Arizona State University, thinks transit service, especially bus transit, is so poor in the U.S. partly because it's treated as a social or public service—a form of government support or assistance for disadvantaged people. Nationwide, transit riders are more likely to have lower incomes than drivers, and among people who ride, those who take the train tend to have higher incomes than bus passengers. Bus riders are more likely to be people with no other option.

"We usually call them transit-dependent riders," says Candace Brakewood, an associate professor in the department of civil and environmental engineering at the University of Tennessee, Knoxville. "They often are low income, can't afford a car or perhaps have a disability, and can't drive or really don't want to drive." Research shows, however, that if service is bad enough, even those who are ostensibly transit-dependent will find other ways of getting around, such as walking, biking, hitching rides and using informal transit networks.

In many cities, buses are treated as critical infrastructure. Take Bogotá, Colombia, for instance, which has no metro service and has roughly the same size population as New York City. The bus rapid transit system, TransMilenio, has priority lanes that shuttle passengers faster than private cars during peak traffic periods. Sleek, well-lit stations were carefully planned to be accessible by sidewalk as well as by bicycle. It's estimated that immediately after launching in 2000, TransMilenio helped to cut air pollution by as much 40 percent in certain locales, reduced car fatalities by 92 percent, and even seduced some commuters into giving up their cars—11 percent of riders identify as former drivers.

Higashide points out that when transit is safe, reliable and fast, like it is with TransMilenio, it can feel like a public luxury. That term, whose recent popularity traces back to writer and activist George Monbiot, refers to services and experiences that feel luxurious

ChandraDhas/Getty Images

but are intended for public consumption. Instead of private pools, it's public pools that are clean, properly staffed and open during the hours when you'd actually like to go. It's big, keystone parks such as Griffith Park in Los Angeles and Central Park in New York, but it's also the well-tended neighborhood playground with swings that glide effortlessly. At its core, public luxury is the idea that "the good stuff" doesn't have to be locked up in private ownership. Owning a car, after all, comes with its own set of headaches. A bus system like TransMilenio makes choosing transit over driving almost pleasurable rather than a sacrifice.

In addition to running fast and frequently, a bus system that feels like a public luxury will have routes that take riders to the places they want to go (the movies, a friend's house, a museum), as well as the places they need to go (work, the doctor's office). Bus stops will be well marked in safe locations, with seating and protection from sun and rain.

Because most riders get to bus stops by walking, sidewalks and other surrounding infrastructure are needed, too. In 2011 a child in Georgia was killed by a hit-and-run driver while he and his family were crossing the street to get to their bus stop. The stop was located directly across from their apartment complex, but crossing the street via the nearest crosswalk would have meant walking an additional two thirds of a mile.

Well-designed bus systems allow people who can't drive or simply don't want to—such as older people and people with certain disabilities—to get around. They also enable older children and teens who are too young to drive to transport themselves from home to school and to extracurricular activities on their own, freeing up parents' time. And riders tend to have a special relationship with buses in part because of their drivers. "If you're doing a trip regularly, it's nice to know the person you're traveling with," Watkins says. It's the feeling that "they're looking out for you."

BETTER BUSES, BETTER CITIES

BEYOND EMISSIONS, there are other reasons to want fewer people driving. In addition to the climate crisis, we also have "a justice crisis, a safety crisis and an economic crisis, all of which come together on our roadways," King says. Their solutions, he adds, can come from the roadways, too.

It's no mystery that significant investment is needed to make bus transit viable. In 2022 Antelope Valley in northeastern California became the first municipality to unveil an all-electric bus fleet. The upgrade cost roughly $80 million, or about $1 million per bus. But the Antelope Valley Transit Authority notes that the upgrades came with savings—the electric fleet's first 10 million miles saved the agency $3.3 million in avoided fuel costs. The new buses also emitted 59 million fewer pounds of CO_2 over the same distance.

Municipalities aren't the only ones saving money. Cars have long been considered a ticket to the middle class partly because it's difficult to find work in most places without one. On average, Americans spend about 13 percent of their income on transportation; those with the lowest incomes spend nearly 30 percent. Nationwide, car debt totals more than $1.4 trillion and is projected to grow. Buses can reduce economic pressures and increase access to opportunity.

Fewer drivers on the road will also save lives. More than 40,000 people are killed in motor vehicle crashes every year in the U.S. Compared with their gas counterparts, EVs are heavier and can accelerate faster.

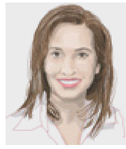
Political will—the risk of angering drivers by giving up public roadways to public transit in particular—is often the biggest hurdle to implementing changes. But Seattle has shown it can be done. "King County Metro in Seattle had a whole group dedicated to speed and reliability," Watkins says. Between 2010 and 2017 the city's ridership grew, bucking nationwide trends that saw bus ridership decline by 15 percent between 2012 and 2018.

At a time when we need to collaboratively act on climate change, Higashide says that riding the bus reminds us that "we're making decisions that affect each other." SA

FROM OUR ARCHIVES

Urban Planning in Curitiba. Jonas Rabinovitch and Josef Leitman; March 1996.

scientificamerican.com/magazine/sa




Susana Martinez-Conde and **Stephen Macknik** are professors of ophthalmology, neurology, and physiology and pharmacology at SUNY Downstate Health Sciences University in Brooklyn, N.Y. Along with Sandra Blakeslee, they are authors of the Prisma Prize–winning *Sleights of Mind.*

Friends Can Make Things Very Scary

Haunted houses reveal how friends and strangers shape our fears

By Susana Martinez-Conde and Stephen Macknik

From Marie Tussaud's Chamber of Horrors to Disneyland's Haunted Mansion to horror-themed escape rooms, haunted house attractions have terrified and delighted audiences around the world for more than 200 years. Today thousands of haunted houses operate in the U.S. alone.

These attractions turn out to be good places to study fear. They help scientists understand the body's response to fright and how we perceive some situations as enjoyably thrilling and others as truly terrible. One surprising finding: having friends close at hand in a haunted house might make you more jumpy, not less so.

In a 2022 study, scientists teamed up with The 17th Door, an immersive haunted experience in Fullerton, Calif. The roughly 30-minute walkthrough at The 17th Door, set in a fictitious penitentiary, has included mimicked suffocation, actual electric shocks, live cockroaches, brief submersion in water and being shot with pellets by a firing squad while blindfolded. Guests are given a safe word to exit the experience: "Mercy."

Psychologist and study co-author Sarah Tashjian, who is now at the University of Melbourne, and her team conducted their research with 156 adults, who each wore a wireless wrist sensor during their visit. The sensor measured skin responses linked to the body's reactions to stress and other situations. When the sensor picked up, for example, greater skin conductance—that is, the degree to which the skin can transmit an electric current—that was a sign that the body was more aroused and ready for fight or flight. In addition to this measure, people reported their expected fear (on a scale of 1 to 10) before entering the haunted house and their experienced fear (on the same scale) after completing the haunt.

The scientists found that people who reported greater fear also showed heightened skin responses. Being with friends, Tashjian and her colleagues further found, increased physiological arousal during the experience, which was linked to stronger feelings of fright. In fact, the fear response was actually weaker when people went through the house in the presence of strangers.

Although Tashjian and her colleagues had initially wondered whether friends might make the experience less harrowing, she feels their study's findings also make sense. "Because the haunted house was entertaining and exciting, as well as scary, it is possible that being with people you know made the entire experience more arousing," Tashjian explains. "There was likely a contagious feedback loop with friends that wasn't as strong among strangers."

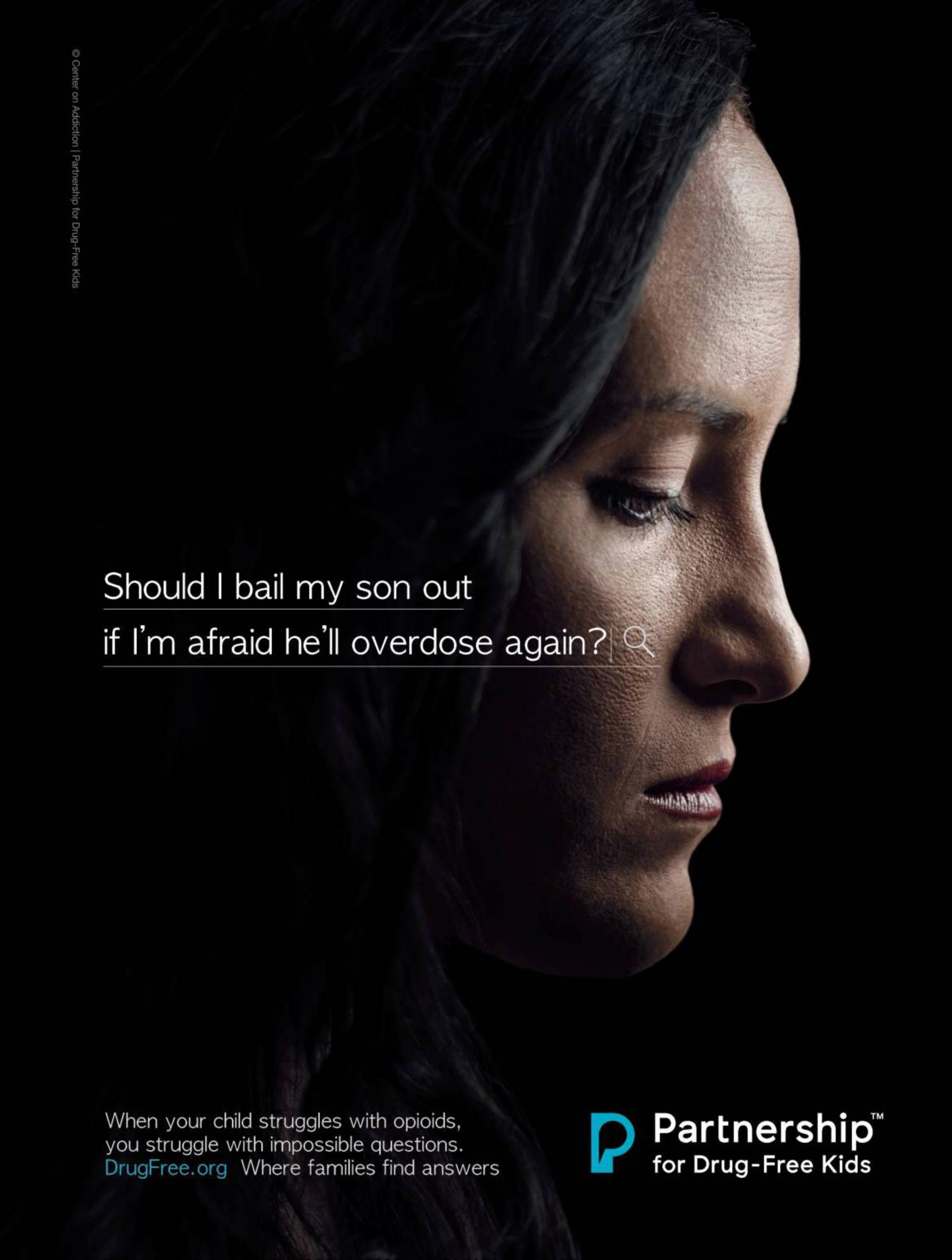
Other investigators have used haunted houses to understand how fear and enjoyment can coexist. In a 2020 study led by Marc Malmdorf Andersen, a member of the Recreational Fear Lab at Aarhus University in Denmark, scientists joined forces with Dystopia Haunted House. The Danish attraction includes such terrifying experiences as being chased by "Mr. Piggy," a large, chain-saw-wielding man wearing a bloody butcher's apron and pig mask. People between the ages of 12 and 57 were video recorded at peak moments during the attraction, wore heart-rate monitors throughout and reported on their experience. People's fright was tied to large-scale heart-rate fluctuations; their enjoyment was linked to small-scale ones. The results suggest that fear and enjoyment can happen together when physiological arousal is balanced "just right."

An earlier study led by Mathias Clasen of Aarhus University also used Dystopia Haunted House to gain insight into how "adrenaline junkies" and "white-knucklers" manage their fear. Some visitors applied strategies to minimize fear, such as closing their eyes. Others sought out scary stimuli to maximize terror. Both groups reported similar levels of satisfaction, suggesting that people upregulate and downregulate their fear arousal for an optimal experience.

Understanding these patterns has real-world benefits. Tashjian notes that learning what factors amplify and reduce threat responses can help people with post-traumatic stress disorder or anxiety. She adds that you can help to consciously regulate your body's fear response "by practicing deep-breathing exercises or meditation [and] mindfulness." These practices can benefit many people facing stressful or threatening experiences in day-to-day life.

But in the meantime, if you want to get really scared at your next haunted house, keep your eyes open, lean into the scary moments—and bring some friends along. SA

Illustration by James Olstein


© Center on Addiction | Partnership for Drug-Free Kids
Should I bail my son out
if I'm afraid he'll overdose again?
When your child struggles with opioids,
you struggle with impossible questions.
DrugFree.org Where families find answers
Partnership™
for Drug-Free Kids

The Blast That Shook the World

A decade ago Earth suffered its largest asteroid impact in more than a century

By Phil Plait

Ten years ago, as the sun rose over Chelyabinsk, Russia, the sky exploded.

On February 15, 2013, an asteroid slammed into Earth's atmosphere at nearly 70,000 kilometers per hour. Almost the size of a tennis court, it blazed brilliantly in the sky as if a second sun had appeared and begun racing from southeast to northwest.

Ramming through the air at hypersonic velocities blowtorched the surface of the asteroid, which left behind a thick trail of vaporized rock as it screamed over Earth. The immense pressure started to flatten it (scientists call this "pancaking"), and the force finally overcame the asteroid some 40 kilometers above the ground. It crumbled into smaller chunks, each one still traveling at more than a dozen times the speed of a bullet fired from a rifle. These fragments also pancaked, creating a series of brief but powerful flashes of light as they heated to incandescence. The remaining pieces vaporized.

All of this happened in mere seconds, with the ultimate blow occurring when the asteroid was about 30 kilometers up. The energy of its last motion was converted into heat in an instant. The resulting huge fireball briefly outshone the sun in the sky, emitting energy equivalent to the detonation of about half a million metric tons of TNT.

The shock wave from this explosion traveled away from the blast, taking about a minute and a half to reach downtown Chelyabinsk, roughly 40 kilometers to the north. The industrial city of a million people was just starting its day when the apparition blazed across the sky. The awesome spectacle and the long, lingering vapor trail brought people outside or to their windows to see what happened—and that's when the shock wave touched down.

A tremendous thunderclap shattered windows all over the city, and flying glass was the source of most of the injuries to the roughly 1,500 people harmed in the event. Fortunately, no one was killed, and infrastructure damage was relatively minimal. Had the asteroid been bigger or made of metal or if it had plunged downward at a steeper angle, this story could have been quite different, the aftermath far more severe.

Chelyabinsk was a wake-up alarm for Earth—a loud one.

It was also a major learning experience for scientists, as it was the largest known atmospheric impact since the Tunguska bolide in 1908. The asteroid's smoking trail was viewed by satellites as well as by thousands of eyewitnesses and cameras. Meteorites rained widely, including one monster half-ton chunk 1.5 meters across that plunged into a frozen lake and was later recovered. There's even security-camera footage of that piece crashing, creating a dramatic plume of snow and water shooting up into the air.

The meteorites recovered from the event revealed the asteroid's violent history. Shock veins riddled them, leaving narrow fissures. These showed that the 19-meter-wide Chelyabinsk rock was once part of a much larger asteroid that itself had suffered an impact, which broke off the piece that smashed into Earth and cracked it throughout. Radioactive dating indicated that the first impact may have occurred as long as 4.4 billion years ago, when the solar system was less than 200 million years old. Those fissures in the Chelyabinsk rock weakened it, allowing it to more easily disintegrate high above the ground and create that massive shock wave. The ghostly fingers of an ancient deep-space impact had reached out and touched the lives of thousands of Russian people that day.

It's not clear which asteroid may have been the parent asteroid. Scientists traced the trajectory of the Chelyabinsk impactor backward into space and found consistent matches to asteroids 2007 BD7 and 2011 EO40. One may be the parent body, but it remains uncertain.

An analysis of Chelyabinsk, together with smaller, lower-energy events, showed that these kinds of impactors affect us much more frequently than previously thought. A Chelyabinsk-size impact happens every 25 years or so, with most occurring over the ocean or wilderness areas, thankfully.

It's a bit alarming that astronomers didn't see this asteroid coming long before it hit us. But asteroids tend to be very dark, and small ones are extremely faint even when close to our planet. Just a few years earlier the four-meter-wide asteroid 2008 TC3 became the first one ever detected before striking Earth. Only six others have been discovered before impact since then, including 2023 CX1, which lit up the English Channel on February 13, 2023, as if marking the week's anniversary. All were small, posing no danger to us on the ground.

Now, after I've terrified you about impacts from these objects, comes the good news: we're getting much better at finding them. In the decade since Chelyabinsk, about 20,000 near-Earth asteroids have been discovered—more than had been found in all of history up to 2013. New survey telescopes such as Pan-STARRS and the Zwicky Transient Facility have come online, and better detection and analysis techniques have been developed that accelerated the rate of discovery. Soon the huge Vera Rubin Observatory and NASA's NEO Surveyor space mission will also significantly boost the number of known Earth-threatening asteroids.

Finding them, though, is just the first step. Doing something about them is the next. To that end, in November 2021 NASA launched the Double Asteroid Redirection Test (DART) mission, which slammed a half-ton impactor into the 170-meter-wide asteroid Dimorphos—a moon of the larger asteroid Didymos. The momentum from the collision changed the orbital period of the asteroid by more than half an hour. That was an even bigger shift than had been predicted—a vast plume of material that the impact excavated and flung away from the

Phil Plait is a professional astronomer and science communicator in Colorado. He writes the *Bad Astronomy Newsletter.* Follow him on Twitter @BadAstronomer

Contrails left by the Chelyabinsk meteor over Russia

Alex Alishevskikh

asteroid's surface added a kick—showing that it's possible to use such a spacecraft to alter an asteroid's trajectory.

Bigger blasts might be able to divert an incoming space rock as well. Detonating a nuclear weapon near a small asteroid could vaporize much of its surface. This hot vapor would rapidly expand, acting like rocket exhaust and pushing the asteroid into a new and, one hopes, safer trajectory. Some issues regarding this method are still fairly difficult to overcome—it's currently illegal under the Outer Space Treaty to explode nuclear devices in space, for example—but a dangerous asteroid headed our way might grease the skids a bit on a political fix.

Since the Chelyabinsk impact, two spacecraft have not only approached small asteroids but also collected samples from them; one, Hayabusa2, already dropped off its samples back at Earth, and the other, OSIRIS-REx, will do so later this year. Both asteroids, Ryugu (roughly one kilometer across) and Bennu (500 meters across), are essentially rubble piles, loose collections of small rocks held together by their own meager gravity. It's likely all small asteroids are rubble piles, which will affect how we fend them off; their weak structures mean they can absorb the impact of a spacecraft more easily. Imagine trying to punch a box of packing peanuts, and you'll get the idea. The DART mission showed, however, that copious amounts of material are ejected after a collision, and that transfer of momentum can actually increase the effect of an impact.

Chelyabinsk caught us by surprise, and although such small impacts may still sneak past our guard, we're getting better at finding potential threats from space and learning what we can do if we find one with Earth in its crosshairs. Big, dangerous asteroids are rare, yet we need only look to Meteor Crater in Arizona to see why we need to take them seriously. The explosion from that impact, estimated as 10 to 40 megatons, carved a hole more than a kilometer across in the desert about 50,000 years ago, probably devastating the plants and animals living there at the time. This might be one of the most recent large direct impacts Earth has suffered, but it won't be the last.

Unless, of course, we do something to stop them. SA

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A Tricky Itch to Scratch

When it comes to diagnosing and treating allergies, there are no easy answers

Decades after her father's terrifying death from a bee sting, Theresa MacPhail learned that she, too, had allergies. The surprising diagnosis came after she contracted four respiratory infections in less than a year and made visits to specialists. What caused the seemingly sudden onset of her allergies?

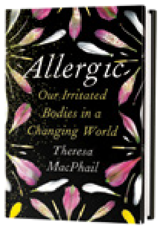
Unimpressed by the books she found in her search for answers, MacPhail, a medical anthropologist, began writing *Allergic* as a "personal and scientific journey to diagnose the problem of allergy in the twenty-first century." The result is a meticulous study of respiratory, food and skin allergies in three parts—diagnosis, theory and treatment—told through patients' stories and expert interviews.

The book begins in doctors' offices, where frustrations abound. People may itch, cough and wheeze in response to allergens without showing an important diagnostic sign of an allergic response: heightened levels of immunoglobulin E antibodies. Others may have positive antibody tests but suffer no other clinical symptoms. Researchers are working on better tests, but MacPhail is focused mainly on the problem of health-care inaccessibility. Even when improved technologies arrive, she says, it is likely that only a few will benefit from them.

When MacPhail shifts from the personal to the global, ambiguity remains. What is driving the troubling upward trend in allergy prevalence worldwide? Perhaps it's because climate change is lengthening pollen seasons, or maybe our modern hygiene habits are removing beneficial microbes from our skin and increasing its permeability. Each theory has its merits and shortfalls, and in combination, they might explain our growing sensitivities.

Treatments come with their own challenges and personal assessments. For a peanut-sensitive child, months of oral immunotherapy starting with very low doses are vital to prevent anaphylaxis, whereas for a man with eczema, instant relief from immune-enzyme-modulating JAK inhibitors may be worth the long-term risk of heart disease. Yet clinical interventions alone won't be enough to control the allergy epidemic fueled by our changing environments. That requires policies that phase out fossil fuels, improve air quality and fund more allergy research into underlying causes.

MacPhail makes the argument that as scientists continue to disentangle the biological complexities of allergies, we also need societal shifts to soothe our increasingly irritated world. *—Fionna M. D. Samuels*



Allergic: Our Irritated Bodies in a Changing World
by Theresa MacPhail. Random House, 2023 ($28.99)

IN BRIEF

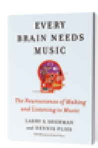
Titanium Noir
by Nick Harkaway. Knopf, 2023 ($28)

Sharp as a shiv but wickedly playful, Nick Harkaway's near-future noir sends Cal Sounder, an all too human detective, into the realm of literal giants. This future's richest people can indulge in titanium 7 rejuvenation therapy, which "turns the body's clock back" to restart puberty, making adults young again—and, with each new dose, increasingly huge. The apparent murder of a titan sets Sounder on a classic hard-boiled mystery case, with a detective's-eye view of the lowest and highest echelons of a fascinating city, plus rigorously imagined speculative genetic science and its consequences. Harkaway's trademarks abound: brisk dialogue, wild set pieces and dead-serious considerations of humanity's next evolution. *—Alan Scherstuhl*

In the Herbarium: The Hidden World of Collecting and Preserving Plants
by Maura C. Flannery. Yale University Press, 2023 ($35)

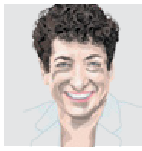
Historically, herbaria—collections of dried, pressed and labeled plants—have been tied to political and economic power. They played key roles in scientific achievements such as Carl Linnaeus's development of binomial nomenclature and Charles Darwin's theory of evolution. Biologist Maura C. Flannery makes a compelling case for reinvigorating the relevance of these "hidden gardens" by exploring their significance as bellwethers of climate change, libraries for biodiversity research, sources of plant DNA, and opportunities to acknowledge and amend the erasure of Indigenous and enslaved people's contributions to botany. *—Dana Dunham*

Every Brain Needs Music: The Neuroscience of Making and Listening to Music
by Larry S. Sherman and Dennis Plies. Columbia University Press, 2023 ($32)



In the 17 years since the popular book *This Is Your Brain on Music* was published, functional MRI has allowed scientists to visualize how music shapes the brain during composition, performance and listening. Now a neuroscientist, Larry S. Sherman, and a professional musician, Dennis Plies, have collaborated on their own version, which puts academic analysis in conversation with feedback from dozens of composers and musicians. Music, the authors write, creates cells in the brain that act like disco balls in a space full of lamps: it "turns your living room into a party every time." *—Maddie Bender*

Illustration by London Ladd



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 *The Big Myth* (Bloomsbury, 2023).

Social Security and Science

Attacks on the program rest on false “facts” similar to ones used against climate change action

By Naomi Oreskes

Whether they work on climate change, evolution, vaccine safety, or any of a host of other issues, scientists frequently face resistance from people offering “alternative facts.” How did we come to live in a world where so many people feel vaguely supported opinions are just as valid as evidence-based scientific research—where people can’t tell the difference between opinion and fact?

Part of the answer involves the long-standing efforts of the tobacco industry to deny evidence about tobacco’s harms and of the fossil-fuel industry to confound understanding about climate change. These campaigns have undermined confidence in the idea that large amounts of scientific evidence produce a more accurate view of the world than do a few dissenting thoughts.

But there’s another source for these doubts: the attack of conservative politicians on the U.S. Social Security program, which gives financial security to senior citizens. Republicans in Congress have recently threatened drastic cuts to Social Security and even privatization. Their ostensible reason is the need to balance the federal budget. “The numbers can’t work” without big cuts to Social Security, former Republican finance committee aide Chris Campbell has declared. In fact, Social Security isn’t a drain on the federal budget; it pays for itself through a dedicated payroll tax.

Why do conservatives keep attacking a successful program that pays for itself? Because of its success. Social Security is “big government” that works. Its accomplishments refute the conservative refrain that federal programs are costly failures and that the government should just leave things to the free market.

Most federal programs that conservatives love to hate were implemented in response to the failures of free markets. In the late 19th century anticompetitive business practices strangled markets and replaced them with monopolies. In the early 20th century one in every 1,000 U.S. workers was killed on the job. In the 1930s millions of able-bodied Americans were thrown out of work and onto breadlines through no fault of their own.

It wasn’t the private sector that fixed these problems. It was government, particularly the federal government. The Sherman Antitrust Act of 1890 was passed to protect competition. Workers’ compensation laws ensured that people injured on the job would receive redress. Laws were passed to limit child labor, expand access to education and—during the Great Depression—rescue American capitalism from a state of near collapse. Unsupported “alternative facts” frequently surfaced in debates over these programs. They appeared in later arguments over Social Security, too.

From its first payouts in 1937 through 1974, Social Security ran in the black; there were never more than two years in a row when the program had to draw on its own trust fund. From 1975 to 1981, however, the program ran deficits, and demographics suggested that things would get worse. In the early 1980s the Reagan administration suggested cutting benefits to make the budget look more balanced—without raising taxes or cutting military spending. This idea emboldened antigovernment ideologues who wanted to eliminate Social Security altogether by giving it to the private sector.

Congressional Republicans passed the baton to a “blue ribbon” committee led by famed economist Alan Greenspan, a libertarian. He has made the case for some privatization by (falsely) claiming that the program was irretrievably broken. Social Security was not in fact broken. Rather, like any 50-year-old thing, it needed some maintenance, and with modest adjustments to benefits and small payroll tax increases, the system was soon back on track.

The antigovernment forces tried again in the mid-2000s, aided by business interests. But polls showed that the more President George W. Bush talked about privatizing Social Security, the less the American people supported him, so he backed down.

Twenty years later we are in a similar place, but reasoned discussion is blocked by ideology that ignores evidence. This is the same fruitless dynamic that stalls action on the climate crisis. Senator Daniel Patrick Moynihan of New York popularized the adage that “everyone is entitled to his own opinion, but not his own facts.” Moynihan could have been talking about science, but he said this during a debate over Social Security. SA

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Illustration by Izhar Cohen

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

MAY

1973 Computer Privacy

"There is growing concern that computers constitute a dangerous threat to privacy. Since many computers contain personal data and are accessible from distant terminals, they are viewed as an unexcelled means of assembling large amounts of information about an individual or a group. It may soon be feasible to compile dossiers on an entire citizenry. However, a computer system can be adapted to guard its contents. Cryptographic encipherment can be achieved in two different ways: by ciphers or by codes. A cipher always assigns substitute symbols to some given set of alphabet letters. A code can convey only meanings thought of in advance and provided for in a secret list such as a code book. Other cryptographic approaches are still being studied."

1923 King Tut's Bountiful Tomb

"Biban el-Muluk, the valley of the kings' tombs, is a wild, desolate region behind the western plain of Thebes. Some 60 tombs in the valley were already known. On November 5, 1922, Howard Carter came upon a step cut in the rock under the path leading to the tomb of Ramses VI. The steps and passages of the L-shaped approach were cleared, leading to Tutenkhamon's tomb. The ante-chamber is the source of practically all the treasures removed this year. When we think of how much still lies within the tomb, it means work for two years or more if they are to be properly conserved, recorded and evaluated."

Classy Vitamins

"The discovery of vitamins was made by [Frederick Gowland] Hopkins only as recently as 1912. The indispensability of these substances is now generally accepted. Three substances of the so-called vitamin class called A, B and C have been differentiated with certainty, and it is possible that more exist. They do not appear to be of one chemical type, and are effective in very small amounts. The green tissues of plants would seem to be the chief site of vitamin synthesis."

Call It Insulin

"A product by the name of insulin has been prepared by Canadian biologists in Toronto, which is claimed to be a specific [remedy] against diabetes. The preparation is made from the pancreas of cattle, sheep and swine."

1873 *Polaris* Lost, Survivors Found

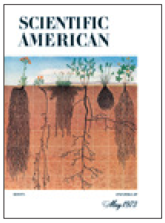
"Telegraphic despatches bring the news of the probable loss of the United States exploring steamer *Polaris* and the end of the Arctic expedition. On the 15th of October, 1872, a party of the crew, some nineteen souls, left the ship to place some provisions on an ice floe. A severe storm came on, causing the *Polaris* to part her moorings; the comrades on the ice, to their dismay, saw their vessel disappear. The tide and wind, it seems, fortunately drove the great floe, bearing the survivors, down through Baffin's Bay and Davis' straits until, on the 30th of April, they were rescued after 196 days on the ice, by the British steamer *Tigress*. The sufferings of the rescued party are described as terrible, but all were in comparatively good health."

Tidal Power

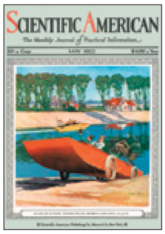
"A trial recently took place of Edward W. Morton's machine, at the East River. The machine works by means of a 'float' which, as it rises and falls with the waves or the tide, propels the machinery to which it may be attached. At the trial it was geared to a saw, and worked with the full rapidity of a circular saw run by steam power, although, perhaps, not quite so uniformly."

Music from Fire

"If into a glass tube two flames be introduced, at a distance of one third the length of the pipe, these flames will vibrate in unison. The phenomenon continues as long as the flames remain separate, but the sound ceases the moment they are brought in contact. If the position of the flames be varied, the sound decreases. M. Kastner has constructed a new musical instrument of a very peculiar timbre, closely resembling that of the human voice. The 'pyrophone' has three key boards; each key is in communication with the conduit pipes of the flames in the glass tubes. By pressing upon the keys, the flames separate and sound is produced. When the pressure is removed, it is instantly stilled by the junction of the flames."



1973



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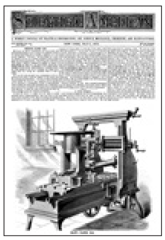
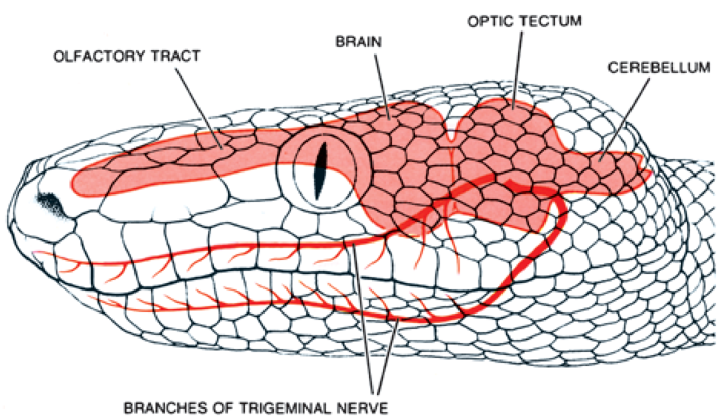


1873



1973, Infrared Boa: "A boa constrictor has sensitive organs that can detect the heat radiation emitted by its prey. When the system detects an infrared stimulus, the trigeminal nerve carries a signal to the brain. A response can be recorded from the brain within 35 milliseconds."

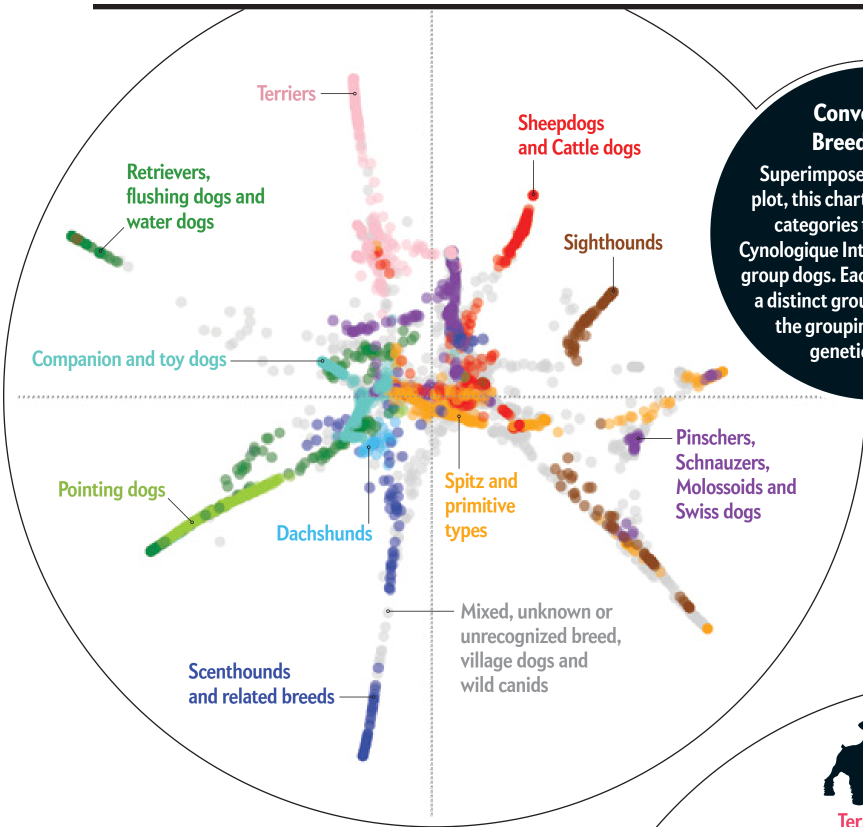
Scientific American, Vol. 228, No. 5; May 1973

Text by Clara Moskowitz | Graphic by Emily V. Dutrow and MSJONESNYC

These two plots show two different ways of categorizing dog breeds—one based on human-defined groupings and another based on "lineages" derived from genetic data. In both plots, each of the 4,000 dots represents an individual dog. Their positions (identical in both plots) reflect how closely genetically related they are to other dogs—two nearby dots are genetically similar, and two distant dots diverge more.

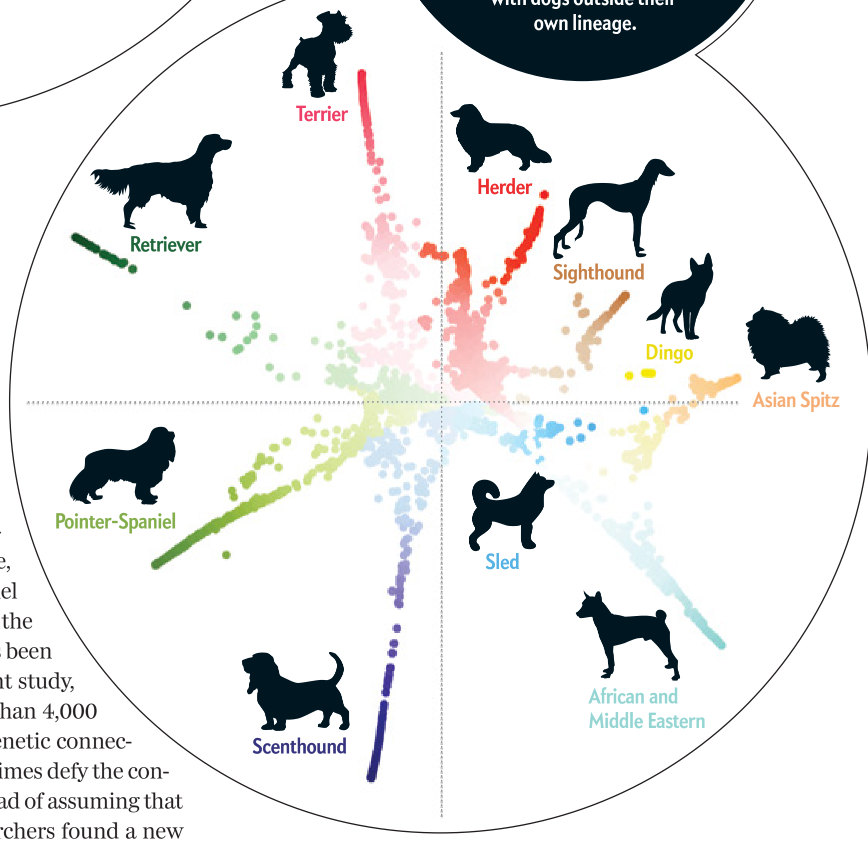
Conventional Breed Groups

Superimposed on the genetic plot, this chart shows the breed categories the Fédération Cynologique Internationale uses to group dogs. Each color represents a distinct group. In some cases, the groupings cover wide genetic territory.



Newly Established Lineages

In this plot, the researchers ignored breed categories and used the genetic data to derive 10 natural groups, or lineages, to organize dogs (*color coded, below*). Dot opacity reflects how closely related a dog is to other dogs in the data set: dark dots are more genetically distinct, whereas light dots often share connections with dogs outside their own lineage.



The DNA of Dog Breeds

When it comes to traits, genetics-based lineages are more telling than breed

There are 356 unique breeds of dog, according to the Fédération Cynologique Internationale, the largest global organization of national kennel clubs. Yet understanding the genetic drivers for the behavioral traits that set these breeds apart has been a long-standing scientific challenge. In a recent study, scientists compiled DNA sequences for more than 4,000 domesticated and wild dogs to uncover the genetic connections between them and found that they sometimes defy the conventional, human-made breed categories. Instead of assuming that some breeds were related to others, the researchers found a new way to group dogs based on their genetics.

The analysis revealed that dogs fall into 10 "lineage" groups with close genetic connections. To see whether dogs in each lineage shared similar traits, the scientists combined their data with behavioral surveys filled out by the owners of around 46,000 purebred dogs. They found that many traits were common among members of each lineage and that certain genetic variants might be related to these traits. "We found a series of genes that turned out to be important in brain development in herding breeds," says Elaine A. Ostrander of the National Human Genome Research Institute, a co-author on the study in *Cell*. "That's a great jumping-off point to study how herding dogs herd."

Source: "Domestic Dog Lineages Reveal Genetic Drivers of Behavioral Diversification," by Emily V. Dutrow, James A. Serpell and Elaine A. Ostrander, in *Cell*, Vol. 185; December 8, 2022 (*reference*)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