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CONTACT

360 W 36th Street, 7S
New York, NY 10018

info@nautil.us

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EDITOR'S NOTE

A Knockout Issue

BY KEVIN BERGER

SCIENCE ELUCIDATES THE WAYS of nature. And those ways are marvelous and strange and surprising. Spooky, too. Although "spooky" may not be the right word for the annihilation of Earth. In our cover story, "The Asteroid Hunters," Christian Köberl, a professor of planetary geology, explains that Earth is "in the middle of a cosmic shooting gallery." That could be a tagline for movies like *Deep Impact*, and "The Asteroid Hunters" has plenty of drama. But it's time to take back the image of asteroids from Hollywood.

That's exactly what writer Tom Vanderbilt does. You will read what the world's top astronomers say about the likelihood of an asteroid crashing into us and learn what scientists and nations are doing to prevent it. I'm not saying you will come away from Tom's absorbing article breathing a sigh of relief. But you will get the uplifting clarity that comes when science clears away myth and misinformation. Science doesn't have the final word on nature. But it does help you make peace with uncertainty.

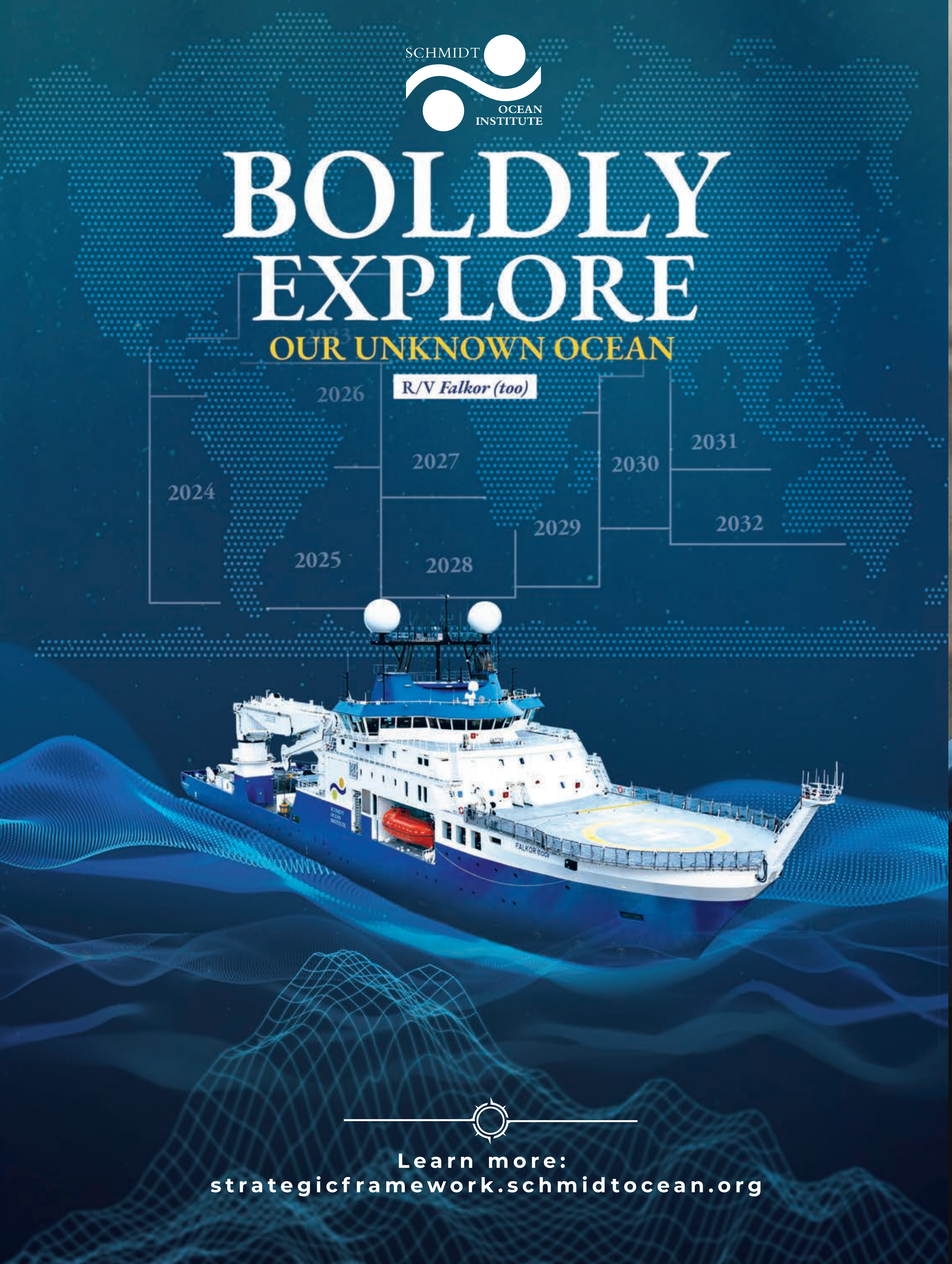
The strange and surprising? That's here, too. You will learn why your brain generates hallucinations when its expectations aren't met. And you will encounter a new gravity theory that challenges Einstein. You will read a story about sperm that is so weird because A) Who in the world writes a whole article about sperm? B) Each tiny sperm has a will of its own in the battle for insemination. It must be cooperative one moment and competitive the next. Sperm, they gotta be smart.

And the marvelous? That's Susan and Joe Sam, an elderly couple in Michigan for whom every day is Groundhog Day. For the past 20 years, Susan and Joe have been watching the groundhogs in their backyard. They aren't scientists, but scientists who study groundhogs have learned plenty from Susan and Joe. You can't read Brandon Keim's article, "The Groundhog Watchers," and see groundhogs as pests, even if they do treat themselves to a few tomatoes in your garden.

There's a school of thought that science journalism should stick to the facts. It's no place to write about personal experiences, set a scene, portray characters. I disagree, and submit as evidence, "The Bittersweet Science."

Author Mark MacNamara, who has Parkinson's disease, puts on the gloves to find out whether "Rock Steady Boxing," reputed to knock down Parkinson's symptoms, is worth the fight. Mark's personal experiences hold truths for everyone. Kimball Magoni, a clinical psychologist who also has Parkinson's, tells Mark that camaraderie is the best medicine. Places like Rock Steady Boxing bring people who feel isolated back into the tribe. They help them build self-acceptance. When that happens for people with Parkinson's, Magoni says, "then you don't care what somebody at the next table in the restaurant thinks of your tremors."

Mark's article is the definition of how a disease doesn't define a person. It's not Mark MacNamara, the Parkinson's victim, that you meet in the article, it's Mark MacNamara, the journalist. Word for word, sentence for sentence, "The Bittersweet Science" is woven with acuity, compassion, poetry, and humor. That's rare in journalism. And precisely why *Nautilus* publishes stories like "The Bittersweet Science."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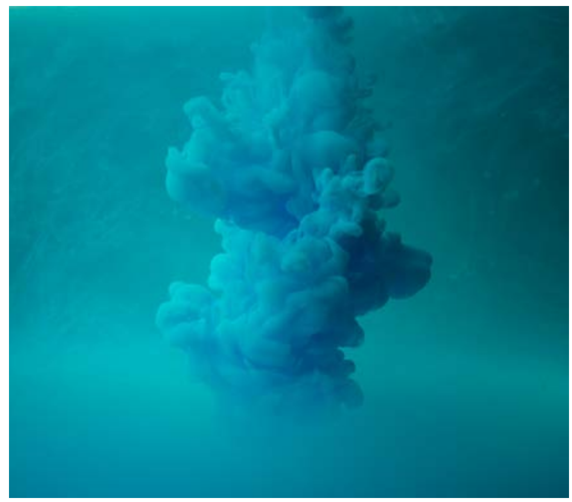
THE PORTHOLE

Short sharp looks at science

MICROBIOLOGY

How Did Life Begin?



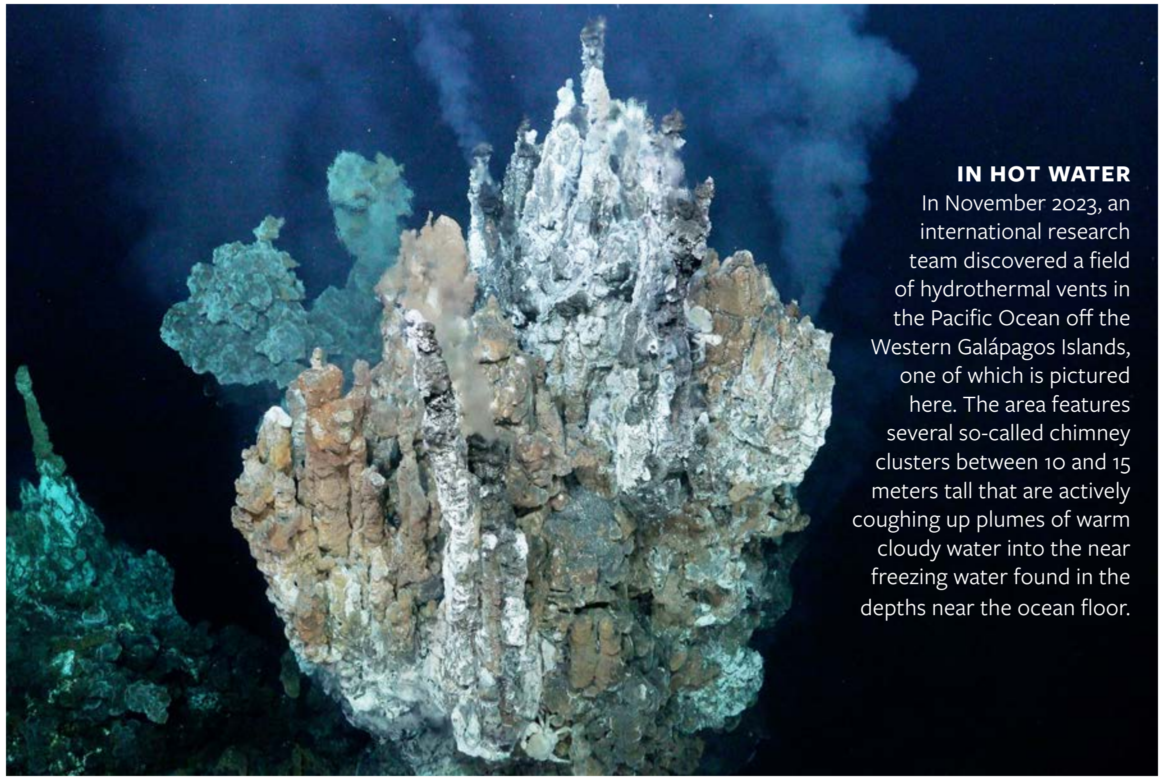
HONCHAR ROMAN / SHUTTERSTOCK

IT IS BIOLOGY'S MOST PRESSING and possibly most confounding question: How did life on Earth emerge some 3.5 billion years ago? Charles Darwin famously speculated that it all began in some "warm little pond"—and it turns out he may have been pretty close to the mark.

Many scientists now believe that primordial hot spots in the ocean floor or in tidal zones, called hydrothermal vents, make the most compelling point of origin for living things. An upwelling of hydrogen-rich alkaline fluids from the vents, which were likely more common on early Earth, could have combined with bicarbonate and carbon-dioxide rich seawater to create excellent conditions for the formation of organic molecules. Recently, scientists, including acclaimed evolutionary biochemist Nick Lane, have shown that amino acids—essential to many biological processes—and primitive cell membranes can form spontaneously around these vents. Others have uncovered some of the world's oldest fossils in areas thought to have been covered in vents long ago. But no one has been able to conjure life from mere chemicals in the lab in any sustainable way.

Now scientists at Newcastle University in the United Kingdom say that by imitating conditions of pressure, heat, chemistry, and flow thought to be found near vents on primordial Earth, they have been able to replicate, for the first time, the formation of long-chain carboxylic acids—also known as "fatty" acids. These fatty acids could have formed the primitive membranes essential to the earliest cellular forms of life, or "protocells."

For their study, the scientists tried to "re-create the core elements of what we think the conditions were like," on early Earth, says biogeochemist Jon Telling of the Newcastle team, coauthor of the paper. They combined dissolved hydrogen with bicarbonate ions in solution, mixed it with magnetite—an iron oxide associated with hydrothermal vents—and placed it in a pressurized flow reactor they had built for 16 hours. The new study differs from earlier efforts, according to the scientists, because of the pressure and continuous mixing, or "flow," they applied to their solution—and because they looked for their organic molecules not in the liquid solution but on a mineral substrate, the magnetite.



IN HOT WATER
In November 2023, an international research team discovered a field of hydrothermal vents in the Pacific Ocean off the Western Galápagos Islands, one of which is pictured here. The area features several so-called chimney clusters between 10 and 15 meters tall that are actively coughing up plumes of warm cloudy water into the near freezing water found in the depths near the ocean floor.

ROV SUBASTIAN / SCHMIDT OCEAN INSTITUTE

> The findings could point to where else in the cosmos we might have neighbors.

The experiment produced a "spectrum" of organic molecules, including long-chain carboxylic acids. It's these long-chain acids—often called fatty acids because they're a key component of body fat—that could have been key precursors to cell membranes. Clusters of fatty acid molecules naturally align themselves in such a way that they have a water-attracting side and a water-repelling side, just as cell membranes do. These clusters also tend to form spherical double shells that are "very similar to actual living cells," says Telling. Water on the inside stays in and water on the outside stays out.

The scientists kept their materials at a temperature of about 200 degrees Fahrenheit—a few degrees below boiling—similar to the temperature they estimate would have existed around hydrothermal vents 3.5 billion years ago. They also applied 16 to 18 times the pressure found in the Earth's current atmosphere, which they calculated to ensure that sufficient hydrogen took part in the chemical reactions. Hydrogen is mostly unreactive at lower pressures, Telling explains, but is an essential component of many organic molecules, including fatty acids.

The higher pressure turned out to be a key to the results, he says. On the primordial Earth that pressure could have been exerted by the water column in a hydrothermal vent a few hundred feet below the surface of an ocean.

The other key was using the mineral magnetite as a substrate for the chemical reactions they wanted to produce. The team found that most of the organic chemicals—including the fatty acids—formed on the surface of the mineral, which facilitated the reactions without getting consumed by them. Telling says previous researchers seem to have expected the products of any chemical reactions to occur within the solution and had looked there without success.

The findings not only help us understand the origins of life on Earth, but point us to where else in the cosmos we might have neighbors, says Telling. The reactions they simulated in the lab could be occurring, right now, on distant moons in our solar system, he says. Saturn's moon Enceladus and Jupiter's moon Europa are thought to have oceans of liquid water beneath their icy crusts, which may harbor hydrothermal vents, heated from their interiors. "These would be really good places to focus future research, to learn about the chemistry of their oceans," he says.

Saturn's Enceladus emits plumes of liquid water from fractures in its crust and probably has sufficient carbon dioxide to form the essential bicarbonates. And scientists have detected organic molecules, both large and small, in these plumes.

The closer we get to understanding the alchemy of primitive life on Earth, the more we may learn about whether and where we have neighbors in the universe, now or at some point in the future of the cosmos.

—Tom Metcalfe

HEALTH

Why I See Static Everywhere

FLICKERING DOTS AND SMUDGES OF LIGHT everywhere, fuzz and static blanketing my visual field, blurring the edges of my reality. For as long as I can remember, this is what I have seen when I look out onto the world. It is as though someone tuned a television inside my head to an unreachable channel, and it got stuck there, or I became permanently submerged in a child's snow globe. But I didn't realize this was unusual until I mentioned it to my partner in a dark hotel room in Scotland a few years ago.

I soon learned that I have a condition called visual snow, a rare neurological syndrome that affects 2 to 3 percent of the global population. Some medical professionals used to believe that it was psychosomatic. Others thought that the condition was caused by drug use, because the visual symptoms overlap with a disorder known as HPPD, a distortion of the perceptual system that can persist months to years after use of hallucinogens. But over the last decade, research has revealed that it is more likely a neurological condition than a psychological one, and that most people who have it never used psychedelic drugs—almost half of people with visual snow report experiencing it since early childhood. Some scientists believe it may be vastly underreported and are still puzzling over the root cause.

CLARISSA WRIGHT

The brain is bombarded by sensory stimuli and has to learn to filter all those stimuli.

In 2014, a set of diagnostic criteria were established for visual snow for the first time: The most central criteria is the snow itself: dynamic dots of light that flicker across the entire visual field for at least three months. But most sufferers also experience at least two of four other diagnostic criteria: persistence of after images (known as palinopsia), excessive floaters, impaired night vision, and sensitivity to or intolerance of bright light. In more severe cases, migraine and tinnitus are also common. Other cognitive disturbances can also arise, such as feelings of detachment from oneself, anxiety, depression, brain fog, insomnia, vertigo, and pins and needles in the extremities.

Neuroscientist Owen White, a professor at Monash University in Melbourne, Australia, first took interest in visual snow in 2012, after a series of patients came to him with some of the strange visual symptoms now recognized as diagnostic criteria for the syndrome. No doctors would take them seriously, his patients told him. White says he has been studying visual snow since and now consults with the Visual Snow Initiative, a nonprofit dedicated to education, research, patient advocacy, and treatment development. White's research suggests that the strange visual symptoms sufferers experience are, essentially, the "noise" that a healthy person's visual system filters out.

"The brain is initially, from birth, bombarded by sensory stimuli and has to learn to filter all those stimuli—a little like noise filtering headphones—in order to produce a coherent signal," says White. But with visual snow, something interrupts the feedback loops in the brain and retina, which interferes with the filtering process, he says.

How and when this malfunction in the visual processing system happens is still unclear. White and others say it may be present at birth, develop in early childhood, or occur after some form of brain dysfunction induced by disease, although there is no clear association with any specific pathology.

Neurologist Christoph Schankin, who also participates in the Visual Snow Initiative, agrees with White and others that the syndrome is caused by a failure of the visual system to filter out noise. He says it all begins with an overamplification of signals from the primary and secondary visual cortices of the brain, which have been shown to respond to the orientation of edges, lines, and objects, as well as color, spatial frequency, and patterns. Schankin has also published research showing that visual snow can be accompanied by not just tinnitus and migraines, but also fibromyalgia, a condition that features musculoskeletal pain, fatigue, sleep, memory, and mood issues. All four conditions—visual snow, tinnitus, migraines, and fibromyalgia—are marked by hypersensitivity to stimuli.

Scientists like White and Schankin are still trying to understand not only what causes visual snow syndrome, but also how to treat the condition, particularly for the most severe cases. For some, it gets worse over time: They may start with visual symptoms alone, but later develop migraine and tinnitus and other cognitive symptoms. Certain drugs have been found to help, including magnesium, cinnarizine, and flunarizine, but no treatments or lifestyle changes so far completely eliminate the visual or cognitive disturbances.

For me, visual snow is more of a nuisance than a debilitating disease, at least for now. But I am an artist, so my eyes are my instrument. They get easily tired, especially when I'm looking at a computer screen or at lights, and my everyday reality often seems out of tune—the reception is bad, the picture unclear. It's worst when night comes. In the darkness, the static is most vivid. But eventually, the scattered stars dancing behind my eyelids drift away, and I sink into the dark abyss of sleep.

—*Clarissa Wright*

PICTRIDER / SHUTTERSTOCK

EVOLUTION

Evolution Led Humans into a Trap

EVOLUTION HAS LED HUMANS into a dark corner, according to a new study. We bonded into groups to solve local problems. Sometimes we shared our solutions with neighboring groups, and they shared theirs with us. The spread of knowledge was a good thing. Culture led to cooperation.

But the scale and impact of human groups has kept growing, and the finite resources of Earth have not. Competition for resources has escalated, and global governance doesn't appear to be in our nature. The authors' conclusion is not a hopeful one: "Ours is a bleak reading of the possibilities of the future of environmental management and human evolution on Earth."

I asked Tim Waring, a professor at the University of Maine and a coauthor of the study, what gives.

As you say in your paper, over the past 100,000 years or so, human adaptation to the environment has been driven by culture. How has this contributed to our current predicament?

In order to understand how the Anthropocene could emerge from an evolutionary perspective, you look at the span of human history, and you have to ask the question: What makes us unique?

We see two strong themes. One is culture, our ability to react to the environment, and then to pass on the socially learned information or behavior we've accumulated, to modify and improve it, test it, and pass it on again. So that gives us cultural inheritance, which we have used to adapt more rapidly to the environment than other species.

The second major theme is that we don't just adapt individually, we do it in groups. Because of the way we share information and cooperate, we're really good at exploiting our shared knowledge as a group to do better than other species can. To not just capture one buffalo, but capture many. To divide up our labor and do agriculture.

Why can't we use this capacity to transcend the current crisis?

My previous research—and my research generally—focuses on trying to understand when humans come together to share limited environmental resources.

> Humans come preloaded genetically and culturally with the willingness to go in on risky endeavors.

We do that all the time. In fact, that is one of the ways that I argue we've dominated the planet. But one of the common factors that determines whether we will succeed at solving environmental challenges, according to my prior research, is scale. The resource in question has to be available at a scale where a group of humans can manage it. If it's too big, we fail. So, for example, ocean fisheries are too big for any one individual nation to control because they are global and every other nation is also harvesting them.

Another factor that has historically made it possible for us to solve environmental challenges is that many individual populations are separately trying to solve the problem at the same time. So one group fails and another group succeeds or succeeds a little bit, and other groups observe this, so we can learn and adapt culturally as a group from the solutions that are out there and improve on them. For example, our modern systems of canal irrigation and reservoirs, with complex dams and gates, didn't emerge overnight. Some groups copied what other groups had done and improved it and improved it again over a long, long period of time. But there is only one global system on Earth.

Another major challenge is that if you look at managing the biosphere, it's an extremely complicated thing to do, really technically demanding and complex. But we don't have a global society or government that can manage it. If we wanted to tax carbon globally, there's no government that can say, "Yeah, we're taxing carbon globally."

Is there anything that gives you hope that we can break out of this evolutionary trap?

Even though the cooperation dynamics do not look good, the fact is that humans come preloaded genetically and culturally with the willingness to go in on risky endeavors with groups of people and to cooperate with them even when the outcome is unknown. We do that again and again. We're also pretty intelligent. But we have to solve this on the first go, and usually it takes us multiple tries to solve big environmental problems.

We don't have time for multiple tries.

We don't have enough time. And we don't have neighboring planets to learn from. If we were able to look at Mars and say, "Wow, Mars did a terrible job with their atmosphere, let's not do that," that would really help.

—*Kristen French*

ENVIRONMENT

What Plants Hear

IT IS NOT THE TREES … that make a wood," the author J.A. Baker once suggested, "but the shape and disposition of the remaining light, of the sky that descends between the trees." Something similar may be true in relation to sound, because the forest also becomes apparent to many sentient creatures through the resonances in the spaces between the trees. The tap of raindrops on leaves, the clack of branches, and the rustle of vegetation shape our sense of what surrounds us. According to the botanist Diana Beresford-Kroeger, the xylem and phloem that transport vital fluids inside trees may be especially long in old-growth forests, and resonate in ways that birds find attractive, encouraging them to nest.

> The root tips of plants act like the brains of simple animals.

Plants reverberate both literally and figuratively. Literally, there is a vine in the Cuban rainforest that has evolved bowl-shaped leaves that act as sound reflectors. The leaves help echolocating bats home in on the vine's flowers twice as fast as they do those of other plants, and in return for a drink of nectar the bats pollinate the vine. Figuratively, the Japanese poet Matsuo Bashō imagines that he hears the sound of temple bells continuing in the flowers after the bells themselves have stopped.

In the poem "A Tree Telling of Orpheus," Denise Levertov imagines a tree that is moved to dance by the musician's song.

But can plants actually hear? Charles Darwin tried to find out by playing a bassoon to a mimosa. He wondered if it might respond by closing its leaves, just as it does when gently touched. The mimosa did not move, however, and Darwin concluded that he had been engaged in a "fool's experiment." His lack of success did not deter a mezzo-soprano named Dorothy Retallack, who in the 1960s showed—to her own satisfaction at least—that plants grow better when exposed to Bach but shrivel under the influence of Jimi Hendrix and Led Zeppelin.

EROSHKA / SHUTTERSTOCK

Retallack's method was deeply flawed, but more refined tests in the 1970s did at first seem to suggest that corn germinates more rapidly when exposed to music of any kind, whether Mozart or Meat Loaf, than to silence. But this finding turned out to be wrong, too. It was actually warmth from the loudspeakers that was making the difference.

By the early 21st century, some researchers were arguing with confidence that members of the plant kingdom are insensitive to sound. Yes, many trees and other plants are exquisitely sensitive to signals passed by others through mycelial networks in the soil, and in other ways. But what advantage could there be for plants in detecting sounds, and how could they possibly do so without brains, or even nervous systems? It seemed like the case was closed.

Except it wasn't. It turns out that plants such as the beach suncup, or beach evening primrose, do hear the sounds of animal pollinators. Using its flowers to magnify and concentrate the sound like an old-fashioned ear trumpet, the suncup reacts to a bee's buzzing wings by increasing the concentration of sugar in its nectar. It does this in less than three minutes—fast enough to make a difference to a bee that has been exploring nearby before it decides to touch down. Even if the bee flies away too quickly, the plant is ready to better entice the next one.

Researchers have also increasingly realized that some plants are remarkably sensitive to vibrations and can discern what is causing them. Thale cress can detect vibrations of less than one ten-thousandth of an inch, or 0.00254 millimeters, in their leaves caused by insects chewing on them, and release a repellent chemical in response. The same plants, exposed to other vibrations caused by the wind or different insects, do not produce more of the chemical. Roots of the common pea plant, meanwhile, can locate water by the vibrations that the water makes when moving inside a pipe even though the soil immediately around the pipe is no wetter than the surrounding soil. The roots then start to grow toward the pipe.

Darwin's original experiment may have failed but, as was so often the case with him, his first intuition was not far off track. When he suggested in his penultimate book, *The Power of Movement in Plants*, that root tips act like the brains of simple animals, he was right. We still understand little as to *how* some plants process sound and organize their reactions to it, but we can add to Shakespeare's figurative "tongues in trees and books in the running brooks" a real world in which some flowers actually hear.

It is also becoming increasingly easy for us humans to listen to the sounds that plants make as they grow and respond to their environment. Microphones placed on the trunk of a tree can capture the sound of water and nutrients channeling through cells: a kind of delicious woody drinking noise. "The sounds of plants are much more fascinating, and challenging to our perception of them, than we have yet to realize," says musician and field recordist Jez riley French. As technologies for listening to them become more accessible, he suggests, there is an opportunity to learn to respect and represent the ecologies of which they are a part with more equity; we can learn that ecosystems that thrive depend on roots and soil, not just on eye-catching leaves and flowers.

—*Caspar Henderson*

Reprinted with permission from *A Book of Noises: Notes on the Auraculous* by Caspar Henderson, published by the University of Chicago Press.

ENVIRONMENT

The Tiny Ant and the Mighty Lion

FEW ANIMALS ARE MORE SYNONYMOUS with the African savanna than the lion. With its muscular stride and ferocious roar, it has long been a symbol of strength, courage, and nobility. As an apex predator, it sits at the top of the food chain—the only real predator it must fear is the human. But recently, one of the savanna's tiniest inhabitants, one that is barely visible, has fundamentally reshaped the fortunes of the lion, as well as those of a number of other magnificent beasts: zebras, elephants, and buffalo.

This real-life fable begins with the iconic umbrella-shaped acacia tree, also known as the whistling thorn tree. Graceful and resilient, the acacia tree dominates the savanna landscape and often provides most of the tree cover for thousands of square miles. Hidden in the branches of this tree are great numbers of tiny acacia ants, which make their home there and act as protectors. With their painful stings and bites, the ants ward off large herbivores such as elephants and giraffes, and allow the trees to thrive.

But lately, the trees have come under the growing influence of a globe-trotting intruder: the big-headed ant. Named for its large heart-shaped head and thought to have originated on the island nation of Mauritius, this aggressive ant has quickly spread across the savanna over the past 20 years, outnumbering and, in some places, eradicating the acacia ant.

Here's where the lion comes in. As an ambush predator, the lion is heavily reliant on the cover provided by the acacia trees. The trees' branches and foliage serve as a hiding place from which the lion can sneak up on its favored prey, the zebra. But without the acacia ant, the acacia trees are susceptible to hungry passersby. When elephants extract the nutrients in the bark and roots with their trunks, the acacia trees are stripped and often left broken. As more and more of these trees are consumed, the landscape has radically changed, becoming open and bare.

Conservationists, noticing the change in tree cover, have worried lions might struggle to capture their prey

JEN WATSON / SHUTTERSTOCK

In areas invaded by the ants, the lions changed their diets.

and feed themselves—and begin to die. With nowhere to hide, how would they get their dinner?

Recently, an international team of biologists set out to answer this question. They collected data about ant invasions; tree cover; zebra, elephant, and giraffe populations; and the behavior of lions and their prey across the 300-square-kilometer Ol Pejeta Conservancy in northern Kenya. What they found surprised them, says Douglas Kamaru, a University of Wyoming Ph.D. student and the lead author of a new paper about their study.

Kamaru and his colleagues expected lions to starve and their populations to shrink, but that's not what happened. "The lion population was stable," says Kamaru. In areas invaded by big-headed ants, the lions simply changed their diets, swapping out zebras for African buffalo. The buffalo aren't as skittish as the zebras, so the lions are less reliant on stealth and surprise.

In 2020, zebra kill occurrence was nearly three times lower in areas invaded by big-headed ants. Zebras also accounted for less than half of total prey kills that year, down from about two-thirds in 2003, while buffalo accounted for 42 percent of all prey kills, up from zero. These changes were unrelated to zebra or buffalo densities, which remained unchanged from 2014 to 2020.

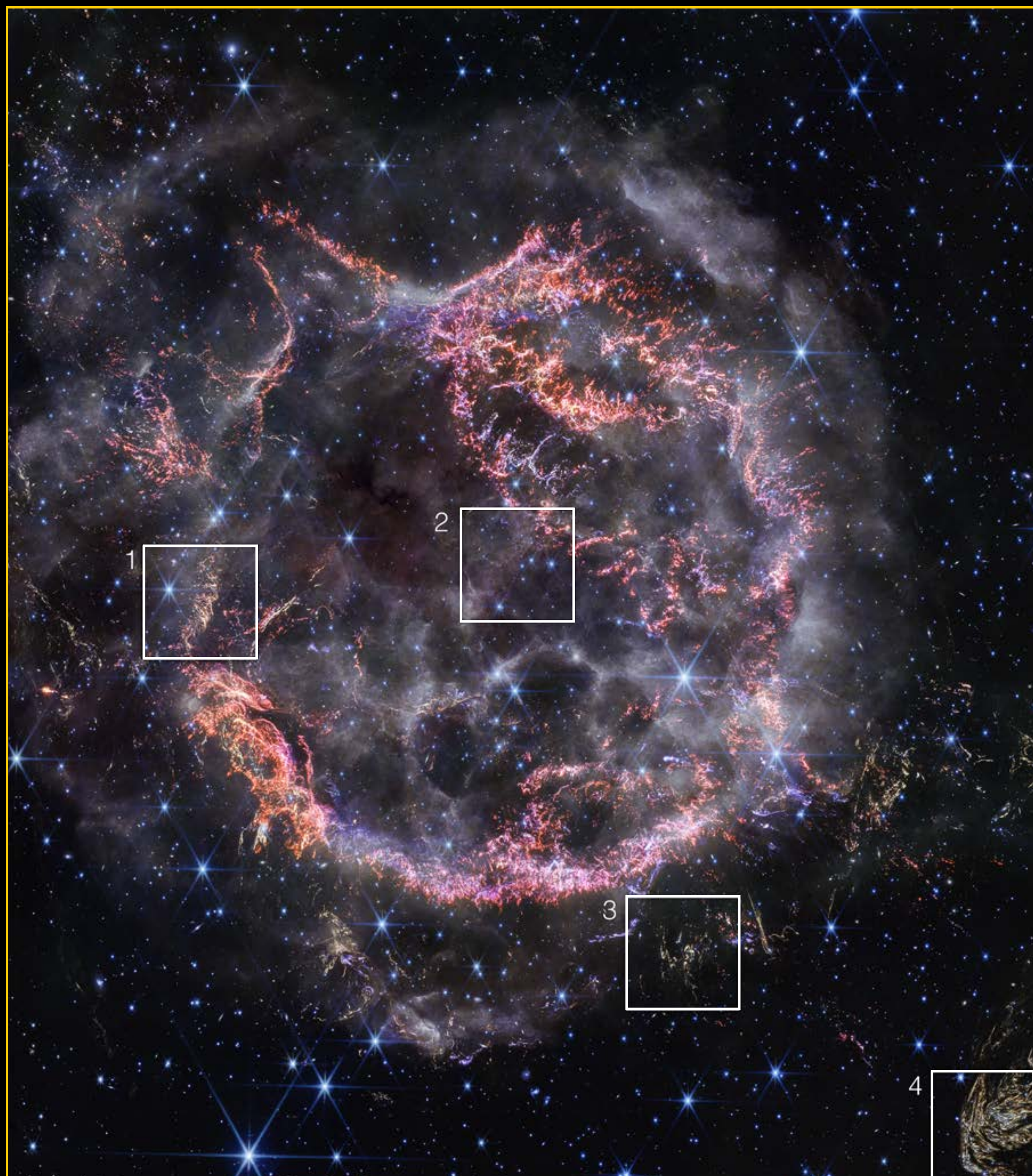
But it's unclear whether the shift from zebra to buffalo can endure. "Going forward, I don't know what's going to happen," says Kamaru. "Hunting buffalo is hard work, and buffalo are aggressive; they tend to stand their ground and fight back. Sometimes they hurt or even kill lions when fighting back. It takes about five lions to bring down a buffalo versus two lions to take down a zebra—the lions expend more energy."

The findings suggest ways to rethink wildlife conservation, says Kamaru. And it involves going beyond species-level evaluations.

"Elephant conservation, lion conservation, rhino conservation—we're concentrated on species, but we have all these other connections because ecosystems are interconnected. There are so many things going on," he says. "We might think that this is just an ant; just a tiny organism we can barely see—but this is exactly what we're trying to look at more deeply."

The ant and the lion offer a dramatic example of the ripple effect—how a seemingly diminutive change in a web of relationships can fundamentally alter an entire ecosystem. The tiniest creature can upset the mightiest beast on the land.

—*Summer Rylander*



Inside an Exploded Star

BY KRISTEN FRENCH

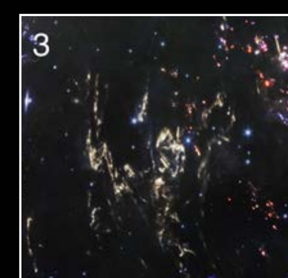
CASSIOPEIA A IS ONE of the most thoroughly studied supernovas in the cosmos. It spans 10 light-years across, or 60 trillion miles. Over the years, numerous ground observatories and telescopes have assembled pictures of the remnants of this exploded star. Now the James Webb Space Telescope is providing a new high-definition look at Cas A.

The near-infrared image shown here, with insets, was taken in December and offers some clues to the dynamics of the dying star's explosion. It shattered almost like glass, leaving behind tiny shards of star material, explained Danny Milisavljevic of Purdue University, who leads the research team, in a NASA communique.

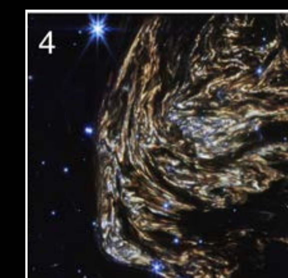
Stars burn nuclear fuel at their cores, generating outward pressure that resists the inner squeeze of gravity. But when a star runs out of fuel, it cools rapidly and can no longer resist that gravitational pull. The star rapidly collapses, which sends out shock waves that cause the outer part of the star to explode. The dense core usually remains, surrounded by an expanding cloud of hot gas called the nebula.

Tiny knots of gas, made of sulfur, oxygen, argon, and neon from the star itself are shown here in bright pink and orange. Some strands of debris are less than 10 billion miles across and too tiny to be detected. Researchers say these strands provide evidence that the star's explosion was akin to the shattering of glass.

Circular filaments of white and purple seen here represent ionized gas found within the so-called Green Monster, a whorl of green light in Cas A's interior that does not itself appear on this image. Researchers believe debris from the explosion of the star chiseled these white and purple circles into the gas emitted by the star before the explosion.



One of a few visible light echoes, which occur after light from the star's explosion heats up cosmic dust, which then glows as it cools down.



Nicknamed Baby Cas A, this large, striated splotch represents a light echo located about 170 light-years behind the exploded star.

NASA, ESA, CSA, STSCI, DANNY MILISAVLJEVIC (PURDUE UNIVERSITY), ILSE DE LOOZE (UGENT), TEA TEMIM (PRINCETON UNIVERSITY)

The Asteroid Hunters

Meet the astronomers with an eye on the end of the world

BY TOM VANDERBILT

BACK IN THE EARLY 1990S, Dave Tholen, an astronomer at the University of Hawaii, had an intellectual itch he couldn't quite scratch. His specialty was finding and mapping asteroids—he had even served on an early "detection committee" that NASA had helped organize. The committee had recommended that Tholen search for asteroids in what's known as the "opposition region" of the sky—the part opposite the sun, with Earth in between—because that's where their models had suggested most asteroids might be found.

Tholen, however, had other ideas. "It seemed like circular reasoning," he told me. "You're basically saying that the best place to look in the sky is where we have been looking." What if, he wondered, he were to search for asteroids whose orbits lay between the Earth and sun? "Something like Venus or Mercury, but on a more eccentric orbit," he described it to me. If it became an impact hazard, he said, "we'd never see it coming, because it's always in the daytime side of the sky."

After years of struggling to secure funding, in 2004 he finally got the opportunity to perform his survey with the Subaru Telescope atop Hawaii's Mt. Mauna Kea. On his last night on the telescope, he and a colleague spotted something moving quickly, typically the dead giveaway of a near-Earth object. They immediately flew to Arizona, where they continued their observations on Kitt Peak. But instead of picking up what they'd seen in the upper left quadrant of their instrument's viewing screen—where they expected it—they spotted something in the lower right. The next night, further observation confirmed their initial suspicions: It was the same object they'd observed in Hawaii. The two sent their data to the Minor Planet Center, which christened the asteroid "2000MN4."

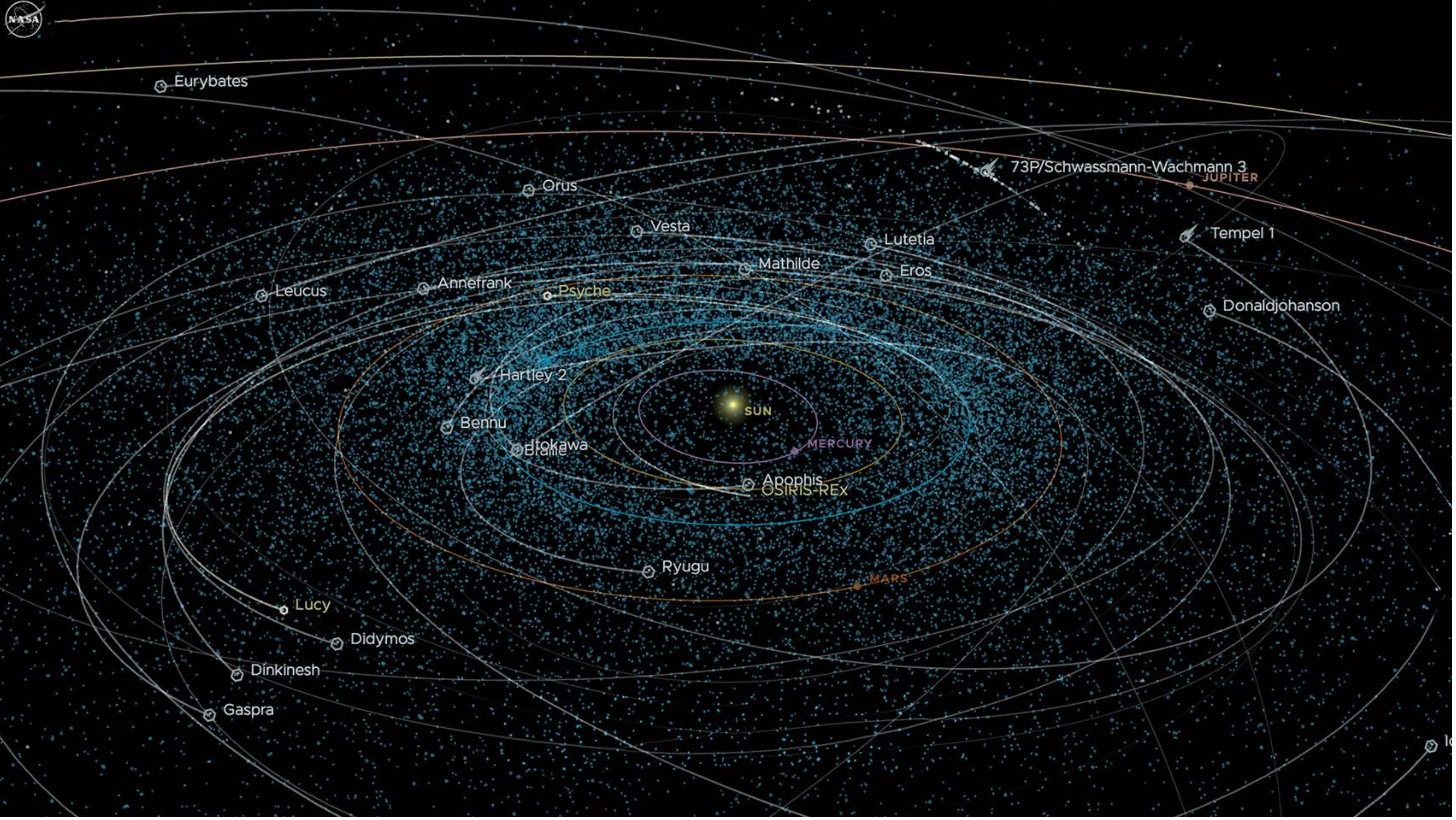
As more observations came in, and more computations were made, a realization dawned, Tholen said. "Hey, this is going to come really close in 2029, so close it could hit." The asteroid was rechristened "Apophis"—the Greek name for an evil Egyptian deity. It was an estimated 1,300 miles in width, bigger than the object that streaked into Russian skies in 1908, unleashing 550 kilotons of downburst and obliterating 772 square miles of Siberian forest (the atmospheric pressure in Britain was affected). If Apophis were to hit, the blast force could be on the order of 1,000 megatons of TNT—the equivalent of many nuclear weapons, felt at once—flattening hundreds of square miles and, if it were to land in a densely populated region, killing millions.

Apophis, projected to have a 1 in 62 chance of striking the planet, surged to Level Four on the Torino Scale, a system developed to measure the risk posed by asteroids to Earth. This level indicates "a close encounter, meriting attention by astronomers"—virtually panic stations in the Near-Earth Object world. Astronomers globally scrambled to make calculations, while *The New York Times* wondered if "Apophis deserves to be added to our regular list of doomsday worries." Soon, though, the threat began to diminish, as further calculations with optical and radar telescopes determined that its impact trajectory was merely a "close approach."

Apophis was downgraded to level zero, becoming just one rock among many, orbiting the sun. Like an aging pop star, it fell off the "Risk List" of the European Space Agency's Near-Earth Objects Coordination Centre—the *Billboard* charts of potential inter-planetary hazard. But in 2029, on Friday, April 13, Apophis will pass within 19,794 miles of Earth—that's closer than the satellites that bring you your cable TV. It's the biggest, closest asteroid to ever come our way with advance notice, visible to the naked eye. Tholen said that while Apophis's current trajectory is not a cause for concern, its ultimate course is forever tinged with cosmic uncertainty, due to fluctuations in sunlight that give slight pushes to an asteroid, and other unpredictable gravitational phenomena.

Which means the asteroid will perpetually lurk on the margins of attention for the next generations of astronomers. "Can the tidal pull of the Earth change the shape of the asteroid? Can it change the spin state of the asteroid?" Tholen asks. "I'm going to take a wait-and-see attitude."

This has been the narrative that most of us know of modern near-Earth-object research. An asteroid is detected—it



EYES ON ASTEROIDS Asteroids, mostly rocky bodies, are remnants of our solar system's formation. Currently there are more than 1.3 million out there. Some of the most prominent are named here, such as Vesta, one of the largest at 329 miles in diameter. This image is from a NASA visualization that tracks asteroids in real time. Explore it on NASA's website, "Eyes on Asteroids."

NASA/JPL-CALTECH

PAGES 22-23: ASTROSTAR / SHUTTERSTOCK

could be new, it could be something old, showing up in a new place. Its trajectory, deemed to come uncomfortably close to Earth, gives it an alarming-sounding ranking on a scale none of us really understand. The media responds with provocative headlines and shots from movies like *Deep Impact*. Gradually, science does its thing and determines the risk to be marginal. The world, like all the objects floating around it in space, moves on.

But tracking asteroids is less a game of absolute uncertainty than reducing uncertainty. Apophis was a false alarm this time, but maybe on its next approach—when you and I and Dave Tholen will have shuffled off this mortal coil—the numbers in our cosmic casino will come in differently. As someone who has actually dreamt of an asteroid striking the Earth (it's not as uncommon a dream as you might think), I find this long game deeply fascinating.

In 2023, I set out to meet the people who spend a good part of their day thinking about a problem that seems quite far down in the global "hierarchy of needs." Which it is—until it isn't. How many other threats in the modern world, manmade or natural, can be said to be extinction-level events? After years of fevered discussion in small rooms, drafting out-there ideas via back-of-the-napkin sketches, scientists are finding a way to address this threat, literally, head-on. I wasn't sure if this was sci-fi wargaming—fantasy football for the interstellar-minded—or an ultimately hopeful sign that the world, in the face of this, and other, imminent threats, could pool its collective intelligence to save itself.

CURRENTLY, ACCORDING TO NASA, there are 1,350,837 known asteroids in our solar system. The number, detailed on an agency web page, increases slowly but regularly, like one of those "Days Since Last Accident" signs in a factory, as astronomers continue to pick them out of the heavens. The bulk of these "rocky, airless remnants," as NASA terms them, are dispersed throughout what's known as the "main asteroid belt," the torus-shaped sea of ancient flotsam between Mars and Jupiter.

Around 30,000 asteroids are designated "Near-Earth Objects," meaning they have a trajectory that brings them within 0.03 astronomical units—around 28,000 miles—of Earth. Most of these asteroids will sail harmlessly by Earth; and yet, over the last 100 years, there have been two meteor-caused atmospheric blasts that, had the geography and population density been a bit different, could have flattened entire cities and killed hundreds of thousands of people. Then there are all those space rocks that are too small to count. Some 100 of these palm-sized objects—call it space hail—survive their fiery descent and hit terra firma every day. Christian Köberl, a professor of impact research and planetary geology at the University of Vienna, told me that Earth, owing to its gravitational pull, is "in the middle of a cosmic shooting gallery."

And yet, it wasn't long ago that the threat of asteroids was barely on NASA's radar. In 1980, the organization was aware of only 51 near-Earth

If the big one comes, and we stop it, we can trace saving the world to the hobbyists.

asteroids. Asteroid detection and defense may never have got off the ground were it not for a handful of scientists and others in the aerospace community who were obsessed by the night sky flotsam. Someday, if the big one comes, and we stop it, we can trace saving the world to the hobbyists.

That same year, Lindley Johnson graduated with a degree in astronomy from the University of Kansas. Today, Johnson is the head of NASA's Planetary Defense Coordination Office. When I met Johnson, he wore a blue pullover marked by an eye-catching embroidered badge that depicts a figure standing atop a castle tower, holding a telescope pointed at the night sky. Below were the words *Hic Sevare Diem*: "Here to save the day." It was designed, Johnson told me, by Michael Okuda, the longtime designer for *Star Trek*. "NASA's not real big on logos," Johnson said, smiling. "But they made an exception."

After college, Johnson joined the Air Force, where he worked on space surveillance systems. In the early 1990s, he was approached by Tom Gehrels, an astronomer at the University of Arizona, about leveraging new digital imaging technology to help hunt asteroids. Conversations with Gehrles and other asteroid hunters like astronomers Gene and Caroline Shoemaker further piqued his interest in tracking asteroids. "This really is a national security issue," he recalled thinking at the time. "Being impacted by an asteroid could be a bad day not only for a particular country, but for the world."

Not long afterward, the Air Force wanted to commission a study of what new capabilities it needed by the year 2020. Johnson stepped forward and said it needed to be prepared for the threat from an asteroid. Air Force staff were nonplussed. But Johnson persevered and wrote "Preparing for Planetary Defense." "I almost didn't get permission to write that paper," he said. His colleagues "thought it was too abstract."

The following year, in July, 1994, the nascent movement had a foundational moment, when the comet Shoemaker-Levy 9 slammed into Jupiter in a destructive rain of fragments. It was the first live viewing of an object from space with a planet. One of the pieces

of the comet ("Fragment G") left an Earth-sized crater. The idea of a momentous impact from space suddenly didn't seem like something for the archaeological record (like the dinosaur-killing impact, 65 million years ago, in the Yucatan Peninsula). "A Threat to the Earth is No Longer a Joke," declared *The New York Times*.

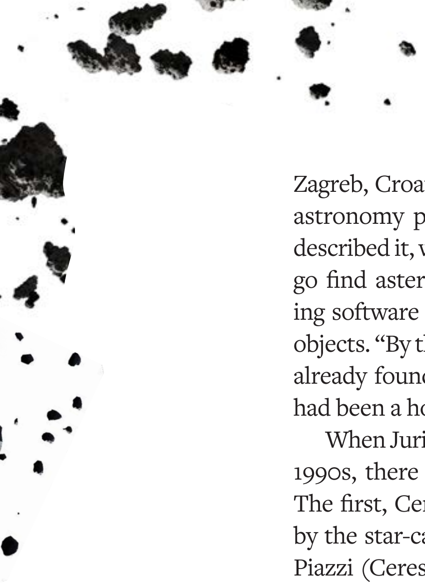
Later that year, Congress directed NASA to search for and track near-Earth objects larger than 1 kilometer. In 1998, the brief was expanded, tasking NASA to create a program "to detect, track, catalog, and characterize" at least 90 percent of near-Earth objects larger than 460 feet in diameter by the year 2020. Johnson helped lead the search effort. But as the deadline passed, the agency had only found a fraction of the asteroids that models suggested existed. "We're only 42 percent complete after 25 years of searching," Johnson said. "At the current rate it'll take another 30 to 40 years to complete the catalog."

ASTEROID, IN GREEK, MEANS "STAR-LIKE," which is how they look at a great distance. Finding them is a bit like the children's game of "spot the difference." You take repeated pictures of the same piece of sky, and "you look for what has moved," said Richard Binzel, a professor of astronomy at MIT. From that blurred trace of light, he explained, you try to determine the asteroid's "orbital elements"—a six-part set of coordinates that reveals not only where it's going, but, by "linking" those coordinates with previous surveys, where it's been. And the longer you watch an asteroid, for months, or better yet years, the better you can determine where it's going. Binzel compared it to a baseball outfielder trying to catch a fly ball. "The ball first comes off the bat and the center fielder's going, 'Do I come in, do I come out?' And then as you see more and more of the path, you are more and more certain."

In 1999, Binzel helped design the Torino Scale. As with the Richter or Saffir-Simpson scale, the idea was to give scientists a jargon-free way of communicating severity. The range goes from Level 0 to Level 10—zero means no chance of collision or will burn up even if it sneaks into our atmosphere; 10 means that you shouldn't even bother running for the hills, which will probably be underwater anyway. Every year, a handful of asteroids get a Level 1 designation, which may start your pulse racing, but it simply means: "A routine discovery in which a near pass is predicted that poses no unusual level of danger."

As more data comes in, these asteroids are typically downgraded to level zero. But often not before a degree of alarmist news attention, exasperating scientists like Binzel. "Basically, a Tesla-sized asteroid passes through the Earth-moon system several times a week," he said. "It's just the nature of the business." The asteroids have always been there, but "we're just now increasingly able to see them."

Mario Juric is one of the world's leading asteroid hunters. A professor of astronomy at the University of Washington, Juric told me asteroids are the reason he's an astronomer today. As a high school physics student in



Zagreb, Croatia, he chanced upon a local DIY astronomy program whose mantra, as Juric described it, was "let's go build telescopes, let's go find asteroids." Before long, he was writing software to automatically find near-Earth objects. "By the time I got to my senior year I'd already found thousands," he says, and what had been a hobby became a career.

When Juric started spotting asteroids in the 1990s, there were only 10,000 or so known. The first, Ceres, had been discovered in 1801 by the star-cataloging Italian priest Guiseppe Piazzi (Ceres is so big that astronomers have since reclassified it as a dwarf planet). "It took us a couple of centuries to get to the first 10,000," he said. "It took an additional 30 or so years to get to 1.3 million."

In the next few years, that number will likely soar to 5 million, largely thanks to an effort—in which Juric has been a prime mover—to build a sky-sweeping telescope at the Vera C. Rubin Observatory in Chile (named for the pioneering American astronomer known for discovering dark matter, among other things). The state-of-the-art telescope utilizes the highest resolution digital camera in the world. It will scan and record the entire night sky every three days, as part of the Observatory's 10-year Legacy Survey of Space and Time. (The Observatory reports science operations will begin in late 2025.) The new telescope will allow Juric to catalog near-Earth objects with unprecedented scope and acuity.

In this work, Juric is getting an assist from The Asteroid Institute, a project of the B612 Foundation. B612, named for the asteroid home of Antoine de Saint-Exupery's eponymous Little Prince, is a nonprofit cofounded by ex-astronauts Ed Lu and Russell "Rusty" Schweickart in 2002 to serve as a kind of planetary watchdog against threats from space. Along the way, B612 has picked up supporters like Queen guitarist Brian May, an astrophysicist who helped start "Asteroid Day," which is celebrated each year on June 14.

Lu, who worked for Google Maps once his space days were over, told me that the effort to build accurate street maps—to use in, say, self-driving cars—isn't so different from tracking near-Earth objects. "Mapping needs to be constantly updated," he said. "At some level, most things don't change, but every once in a while, something does. It's the same thing in the solar system." Unlike ground mapping, however, in space, "everything is moving—you have to talk about trajectories, not locations."

Further complicating matters is the fact that asteroids can go missing. Lu said it is not because "they are changing course drastically," but rather that "in some cases, we don't have a very good estimate of the orbit because we don't have observations of those asteroids over a long enough period of time." And once an asteroid has slipped out of view, the "longer it has been since we've last observed that asteroid, the more uncertain our prediction is of where to look." There are some asteroids that were once known, he said, but now "we couldn't even point a telescope at them."

Lu said, "quite a lot have been lost, the ones that weren't well tracked to begin with." B612 aims to solve this problem by stitching together the past and present observations of the world's telescopes into "one giant unified data set." The longer you've been watching an asteroid, the further into the future you can predict its movement. Asteroid tracking is the ultimate long game.

FINDING AND TRACKING a potentially hazardous near-Earth object is one thing. But what if, to paraphrase Marx, you wanted not just to understand the world, but to change it? Or at least change its orbit.

For decades, scientists, engineers, and others in the planetary defense community have been theorizing on ways to interrupt the journey of an Earth-bound asteroid. One of the theoretical weapons in the quiver is the so-called "gravity tractor," which entails

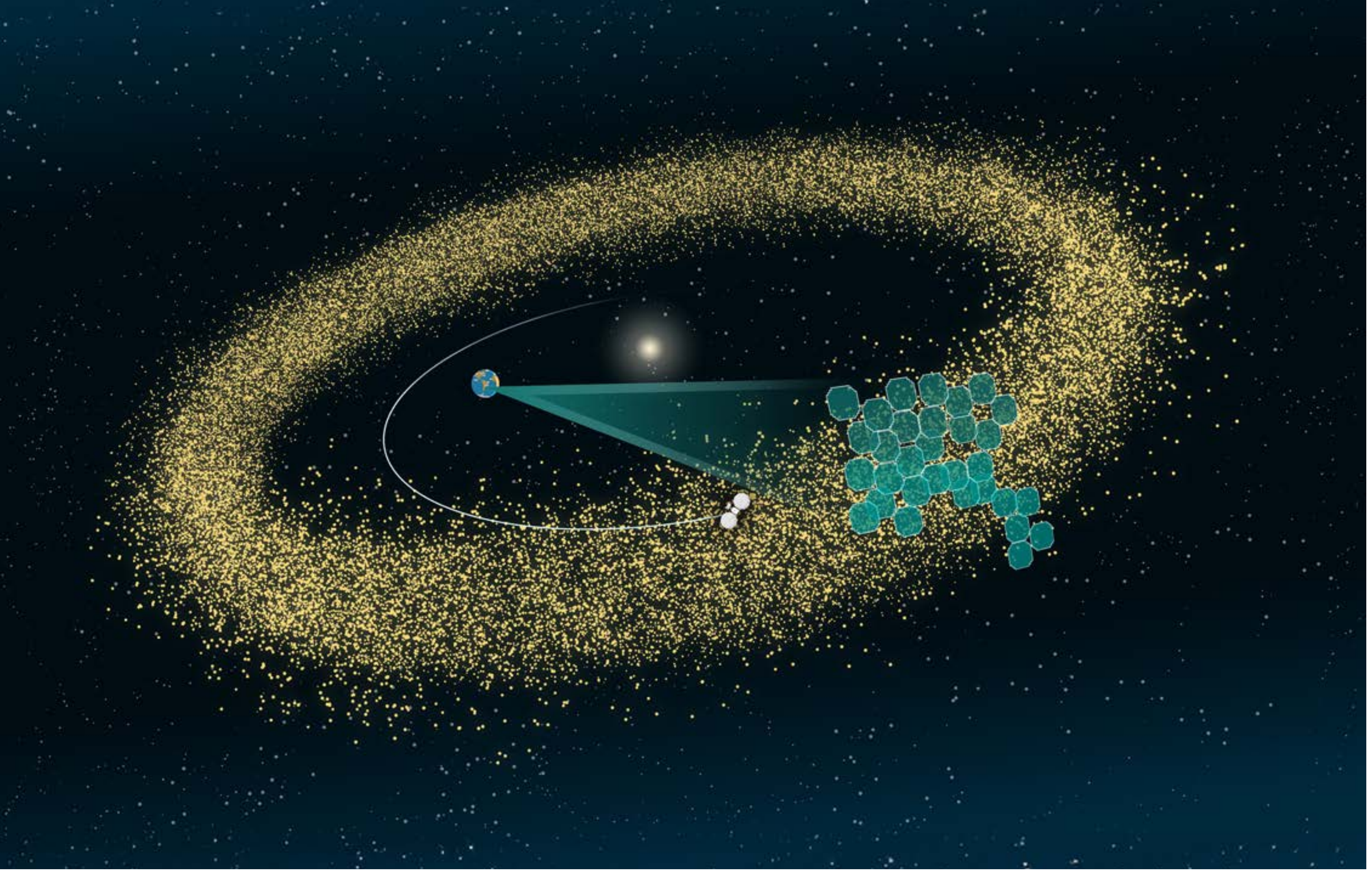
Earth is in the middle of a cosmic shooting gallery.

directing a spacecraft toward an asteroid—not to destroy it, but to travel alongside of it, relying on its gravitational attraction to pull it to a new orbit, like an outer space version of a tugboat shepherding a container ship through New York Harbor. Another is an ion beam "shepherd," in which a spacecraft would direct a high-velocity ion beam (a technology already used to help keep satellites on their proper orbit) toward an asteroid, hitting it with enough force as if the asteroid itself were equipped with an ion booster. Some have proposed blasting asteroids with lasers—not to demolish them, per the video game, but to deflect them. A more low-tech approach involves blasting the asteroid with large "paintballs"—changing the reflectivity of the asteroid which, over time, changes its rotation. Even getting a direct hit on an asteroid that is spinning can be a challenge, which is why one research team advocates a "tethered solar sail," which, when attached to an asteroid, would effectively capture it.

None of these approaches—broadly grouped into "high impulse" and "slow push" solutions—have made it past the theoretical stage. That all changed in 2021 when the first rocket to deflect an asteroid was launched. The target was Dimorphos, a 5-billion-kilogram asteroid moonlet called Dimorphos, orbiting a larger asteroid called Didymos. Dimorphos was the perfect Goldilocks asteroid: sufficiently far away that it posed no actual risk to Earth, but close enough for a spacecraft to reach comparatively quickly.

Nearly a year after it launched, on Sept. 26, 2022, to be exact, the rocket, called DART, for Double Asteroid Redirection Test, smashed into Dimorphos. It was a game of cosmic billiards. NASA shot its cue ball across the solar system at precisely at the right angle to knock Dimorphos off its trajectory. That shot represented a colossal human achievement. "Humanity first moved an asteroid," as Nancy Chabot, a planetary scientist with Johns Hopkins University Applied Physics Laboratory, sums it up. This was, she says, no small task: "It was a huge challenge hitting a small asteroid, which you've never seen before, that's 7 million miles away and moving at 6.1 kilometers per second."

But DART has its limitations. The closer an asteroid comes to Earth, the greater the required angle of deflection, the bigger the force needed



READY FOR THEIR CLOSE UP
In 2025, a new telescope with the world's largest digital camera will come online at the Vera C. Rubin Observatory in Chile. Each turquoise tile represents a group of asteroids the camera's massive lens will capture. Focused on the asteroid belt between Jupiter and Mars (the yellow ring), the telescope will bring asteroids into view with unprecedented detail.

RUBIN OBSERVATORY / NOIRLAB / NSF / AURA / J. PINTO

to deflect. And then there's the size of DART itself: It weighed less than the famed defensive line of the 1985 Chicago Bears. What if an asteroid bigger than Dimorphos, and closer than Dimorphos, was headed our way? "We would need 100 DARTs," explained Andy Rivkin, an engineer with the Applied Physics Laboratory. Or more because some of the DARTS "would probably fail."

Caleb Scharf, senior scientist for astrobiology at NASA's Ames Research Center, has written in *Nautilus* that even a relatively small-scale effort like DART—the "first significant, targeted engineering of the fundamental structure of our solar system in 4 billion years"—could lead to some "entirely unforeseeable emergency problems in the subtle chaos of orbital dynamics." Like a high-order game of billiards, you might sink the eight ball, but end up scratching the cue ball.

ASTEROID DEFLECTION IS NOW a technological reality. But could we—and by we I essentially mean wealthy countries with space capabilities—summon the collective organizational and political will to mount a thoroughgoing defense in the face of a known threat? The specter of climate change suggests that scientific consensus of an actual hazard does not automatically translate into nations taking effective countermeasures.

A Tesla-sized asteroid passes through the Earth-moon system several times a week.

Whatever the technical abilities we might possess to deflect or destroy an incoming asteroid, a host of factors, not the least of which are political, would need to be resolved briskly, and with international cooperation. To game out this scenario, a group called the Planetary Defense Conference—everyone calls it "the PDC"—has gathered biannually since 2004 to think about a problem that is statistically unlikely and entirely plausible.

In spring 2023, I traveled to Vienna, Austria, the site of the latest PDC meeting. In Boardroom D at the United Nations headquarters, Kelly Fast, head of NASA's Near-Earth Objects Observations Program, informed the assembled audience that the agency had detected an asteroid—identified as 2023 PVC—that had a 1 percent chance of impacting the Earth on Oct. 22, 2036.

The audience—comprised of 150 scientists, disaster response managers, legal experts, former astronauts, ethicists—grew quiet, save for the frenetic dance of fingers on laptops. They were seated at long tables that radiated outward in a semi-circular arc, each station equipped with a simultaneous translation headset, some bearing country placards. The room, paneled in Scandinavian blonde wood, exuded a procedural air, maybe the faint whiff of some past war-crimes trial. Through a high window in the corner of the room, a group of badge-wearing visitors looked down.

The risk corridor, Fast noted, extended from the South Pacific to the Southern Indian Ocean, with huge swaths of North America, Europe, and Africa sitting in the impact zone. The damage will be "regional to continental." She added, as if by consolation, "1 percent means there's a 99 percent chance it wouldn't impact."

But what has put NASA on alert—as well as a whole constellation of affiliated governmental agencies and consortiums, ranging from the International Asteroid Warning Network to the United Nations Office for Outer Space Affairs to the Space Mission Planning Advisory Group—is the size of 2023 PVC. Paul Chodas, who heads the NASA Earth Observation program at the Jet Propulsion Laboratory, chimed in. "It could be in the range of 220 to 660 meters. If it's a dark object, it could be much larger," he said. The impact force, Chodas continued, could be in the range of "54 megatons to five and a half gigatons." To put that into context, the atomic bomb dropped on Hiroshima had a blast yield of 15 kilotons—almost a rounding error compared to 2023 PVC.

Lorien Wheeler, who studies asteroid impact risk at NASA's Ames Research Center, told the room to expect "a large ground impact or low airbust causing a highly destructive blast wave and fire." Given the size of PVC 2023, she added, "the damage severities are expected to reach unsurvivable levels." Things hardly get better from there,

DEFENSIVE HUDDLE Destroying an incoming asteroid will require international cooperation. To game out this scenario, scientists from around the world meet annually at the Planetary Defense Conference. Here, in 2023, they meet in Vienna, Austria, at the United Nations headquarters.

TOM VANDERBILT

as gasses, aerosols, and materials are lofted into the atmosphere. "The climate feedback loops would be almost instantaneous," said Lari Mani, with the University of Cambridge's Center for Existential Risk. "Impact winter," she called it.

The end of the world ends with a coffee break. As we sipped dark roast in the hallway, Planetary Defense Conference founder Bill Ailor told me the conference was launched on a whim. Ailor was working for the Aerospace Corporation back in the early 2000s when, he said, "an Air Force general came and basically said, 'suppose an asteroid is headed for Earth? What are we going to do about it?'" At the inaugural conference, someone asked the question of how to notify the White House in the event a serious threat was detected. "There was no path at the time," Ailor said (there now is).

Back in Boardroom D, attendees hashed out a response to 2023 PVC. Brent Barbee, an engineer with NASA's Goddard Space Center, noted that an asteroid deflection mission could, owing to the size of 2023 PVC, require the launch of up to 1300 "Falcon heavies"—SpaceX's signature rocket—to put the asteroid off an Earth trajectory. Anything less than a full deflection could dump the asteroid in an ocean, where it could trigger massive tsunamis.

Noting that anything less than a full deflection could be catastrophic, Detlef Kochny, a planetary defense specialist with the ESA, called for the "nuclear option"—using the blast force of a weapon to shift the asteroid. People had been thinking about using nuclear weapons against asteroids since the height of the Cold War. In 1967, for an exercise in "systems engineering," an MIT professor conducted a seminar that theorized a nuclear counterstrike on an asteroid—1566 Icarus—that was due for a "close pass" of Earth in 1968 (a close pass still being 38 times farther than the moon). The researchers suggested that the six Saturn rockets then in production, each bearing 100 megatons of nuclear explosives, would be required to stop the asteroid—a bit problematic, as the largest nuke in the U.S. arsenal was 25 megatons. There's another problem with the nuclear approach. It is illegal.

"If your vision for a planetary defense mission includes the use of a nuclear weapon, you have a problem," said David Koplow, a law professor at Georgetown University. "Do not go beyond this point without your attorney."

Still, after decades of relative inertia, "planetary defense," said Matt Daniels, assistant director at the White House Office of Science and Technology Policy, "has hit an inflection point." This year, the European Space Agency will launch "HERA," a spacecraft that will autonomously rendezvous with Dimorphos to perform a post-mortem on DART's bullseye and "turn the grand-scale experiment into a well-understood and repeatable planetary defense technique." This year also sees the launch of NASA's Near-Earth Object Surveyor infrared space telescope, as well as the completion of the survey telescope in Chile—two long-awaited instruments that will dramatically quicken the documentation of potential asteroid threats. Spacecraft from the U.S. and Japan are currently returning to Earth, laden with asteroid samples. What might have once seemed a fringe gathering in the small rooms of national laboratories now seemed more like some heady Davos of the near-Earth object scene.

SO ARE THE PLANETARY DEFENDERS ready to *Hic Sevare Diem*—save the day? "The risk hasn't changed," said Johnson, director of NASA's Planetary Defense Coordination Office. "The same asteroids that are there now were there a millennia ago." What has changed, he suggested, "is our understanding of the risk." And it takes a long time, he said, for that understanding to permeate through society. "The lights don't suddenly go on and people understand this is something that the taxpayer's money should be spent on," he said. It doesn't hurt that the universe, once in a while, throws up a reminder.

A few weeks after I returned to my home, in Madison, New Jersey, from the conference in Vienna, a meteor—a "mango-sized rock" as one outlet dubbed it—tore through the roof of a house in Hopewell, New Jersey, with such force that its rebound off the floor tore another hole through the roof. The 4.5-billion-year-old "hammer stone," as such fragments are dubbed when they strike human-made things, landed less than an hour away from me—a mere Planck length in the scale of the universe. It seemed a little coda to the conference, a footnote from outer space: For all our increased power in patrolling the heavens, you can never quite be sure that nothing is going to fall out of the sky.

TOM VANDERBILT is the author, most recently, of *Beginners: The Joy and Transformative Power of Lifelong Learning.*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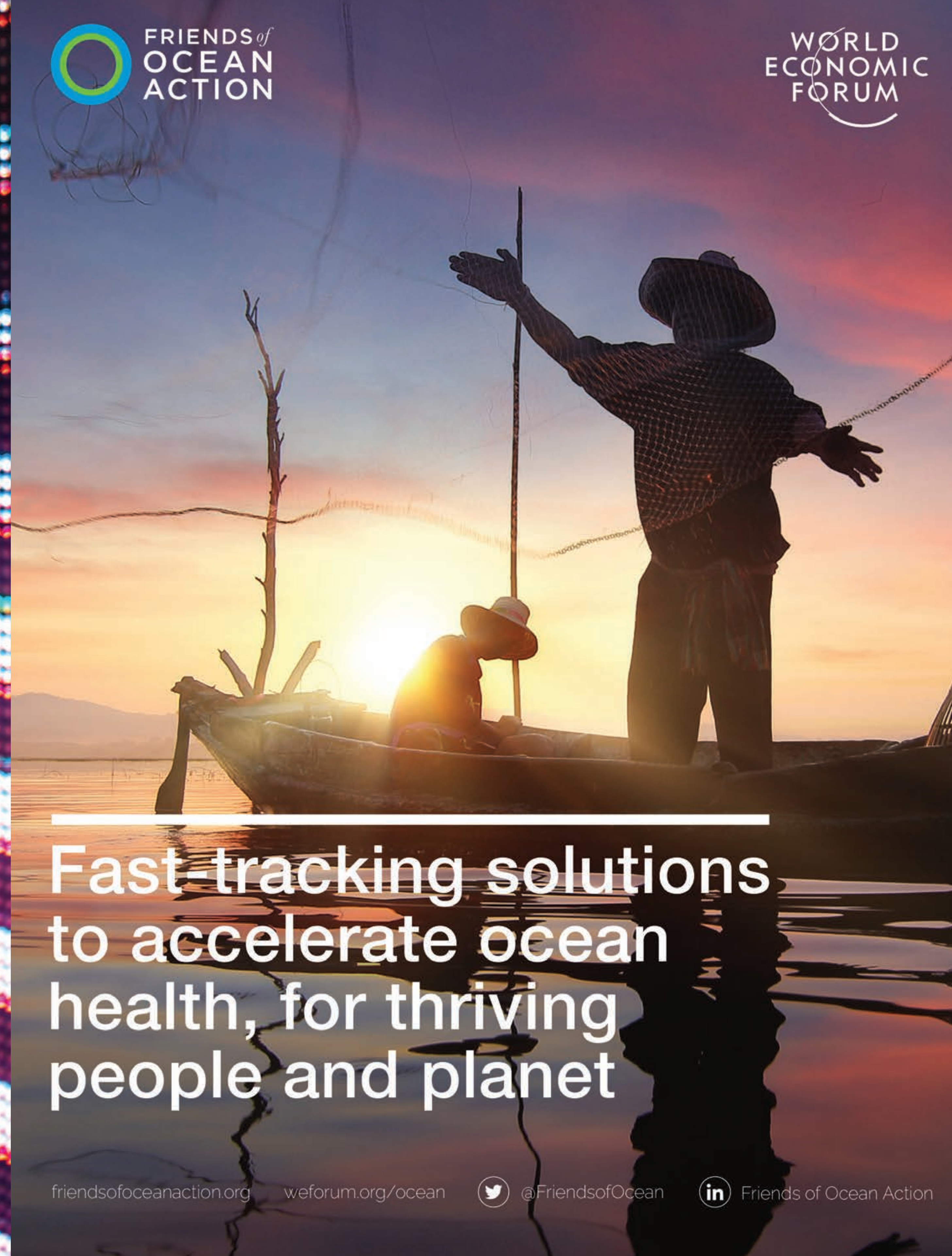
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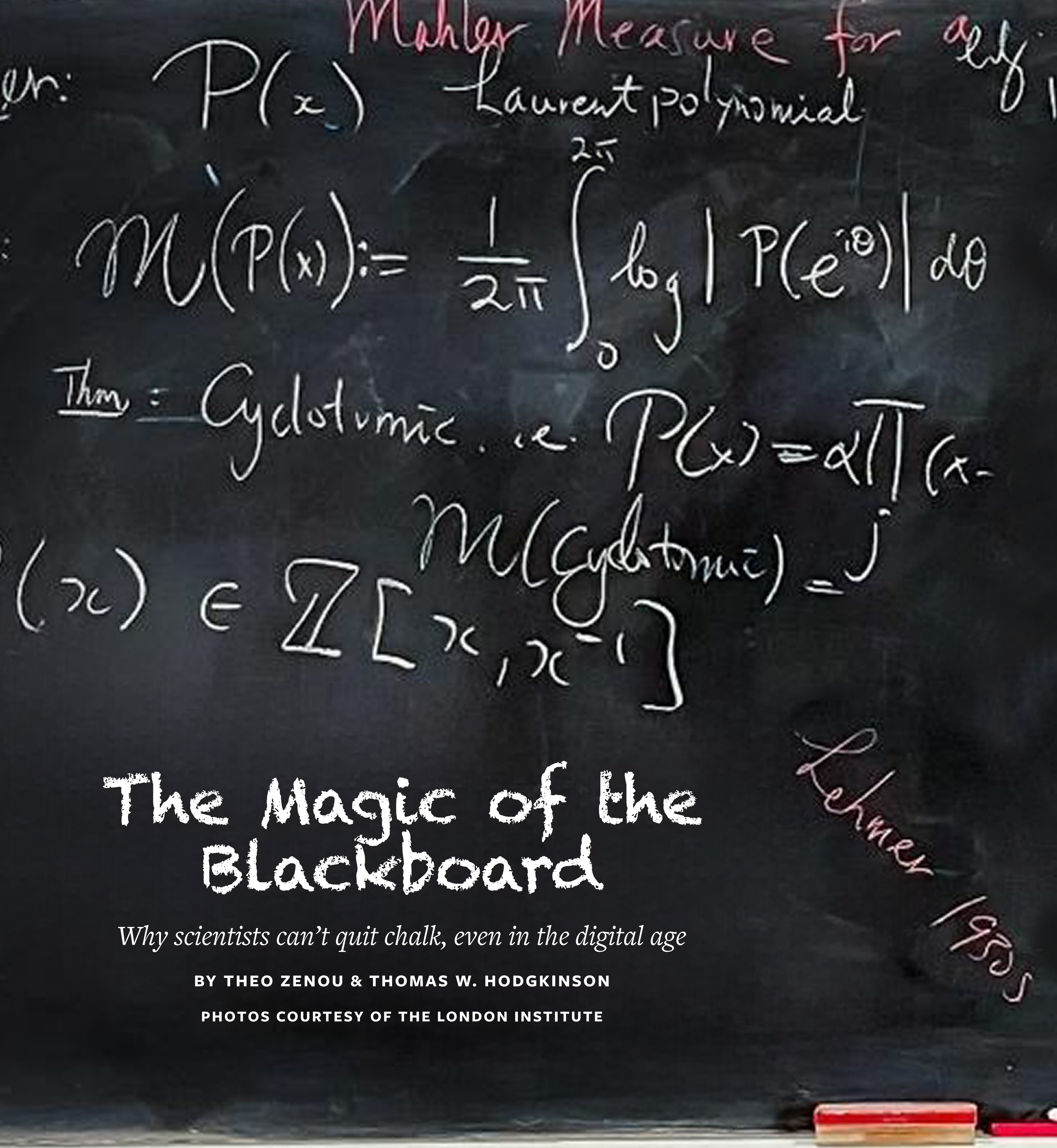

The Magic of the Blackboard

Why scientists can't quit chalk, even in the digital age

BY THEO ZENOU & THOMAS W. HODGKINSON

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IN THE BEGINNING, there is nothing. Then a stroke of white appears. And another. Characters form. Shapes emerge from the darkness. Order out of chaos.

Something magical happens when a scientist writes with chalk on a blackboard. Hollywood directors know this, and have harnessed it in films from *A Beautiful Mind* to *Oppenheimer*. But no one appreciates the power of this venerable technology better than physicists and mathematicians, who infinitely prefer the humble blackboard to its high-tech rivals. The question is, why? What does slate-and-chalk offer, which cannot be simulated by paper or plastic?

"This is a cult that goes back centuries," says Yang-Hui He, a professor at the London Institute for Mathematical Sciences. "When you hold a piece of chalk, and you're looking at a blackboard, it feels like you're doing mathematics, because this is how it has always been done."

The practice dates to at least the 11th century A.D., when the Persian scholar Al-Biruni describes schoolchildren writing on slates. But tradition can't be the only reason why physicists still reach for chalk. After all, few writers today use parchment and quill, even if that's how Shakespeare wrote *Hamlet*.

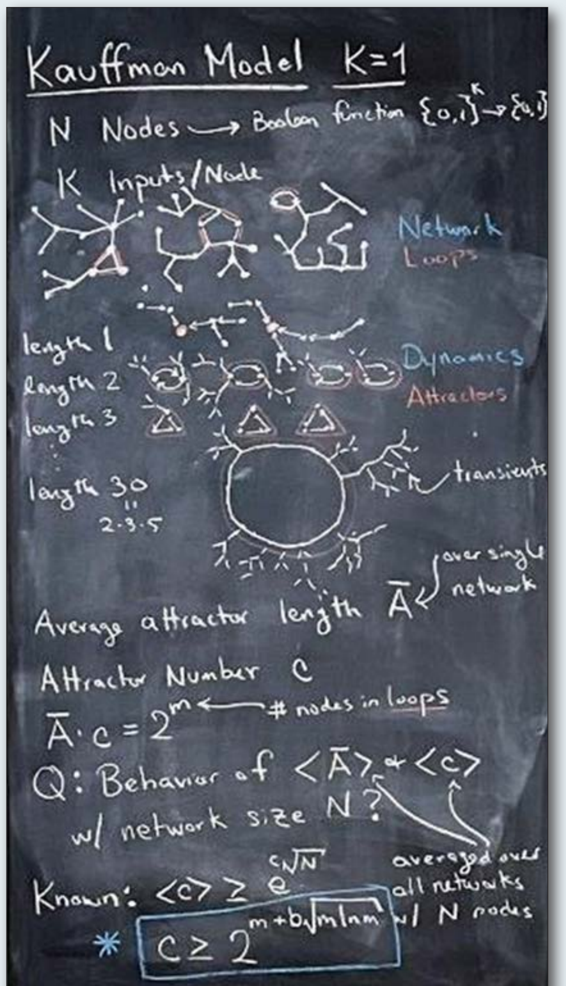
In our quest to understand the timeless allure of blackboards, we've dropped in on our friends at the London Institute in Mayfair in central London. Not affiliated to any university, this rogue band of theorists—the United Kingdom's only independent institute in the mathematical sciences—is devoted to the kind of calculations that are done in chalk.

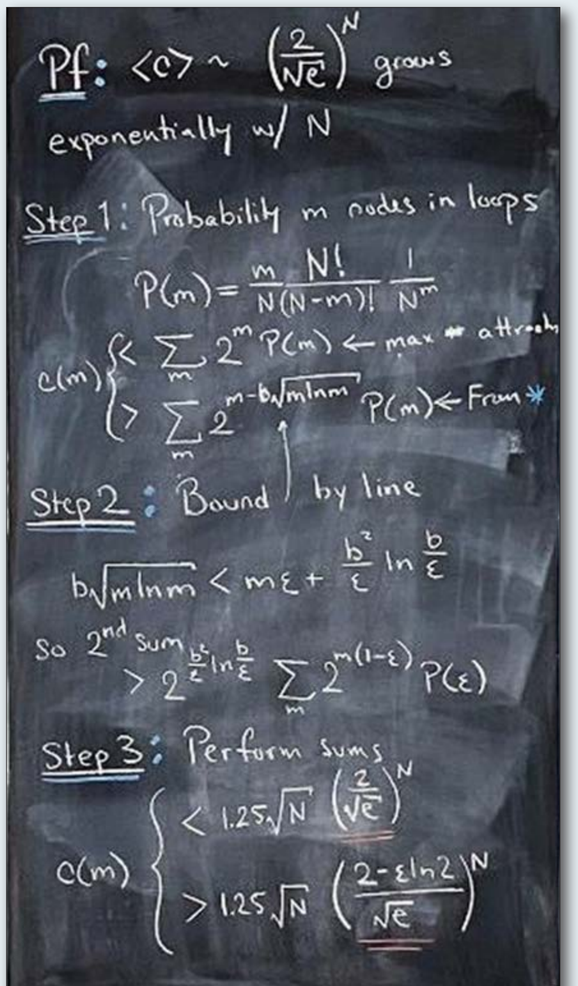
As soon as we walk in, it stares at us: a mighty blackboard, measuring 12 feet by 6 feet, and taking up most of a wall. It's the same in the next room. And the next. Each is dominated by a blackboard, which is either fixed to a wall, or else resting on a pair of easels, like a giant work-in-progress by some ecclesiastical painter. And all of them are covered in runes, riddles, and mathematical scribbles.

"Physics is a process of getting stuck," explains the London Institute's director, Thomas Fink. "Blackboards are the best tool for getting unstuck. You do most of your calculations on paper. Then, when you reach a dead end, you go to the blackboard and share the problem with a colleague. But here's the funny thing. You often solve the problem yourself in the process of writing it out."

To understand why, we talk to Albert Read, author of *The Imagination Muscle*. He argues that imagination is intertwined with acts of creation, of which writing is an example. "You don't imagine something first and then write it down. It's through the act of writing that ideas make themselves known." Scientists at blackboards have "thoughts that wouldn't come if they just stood there, with their arms folded."

When scientists collaborate in chalk, creativity flows.





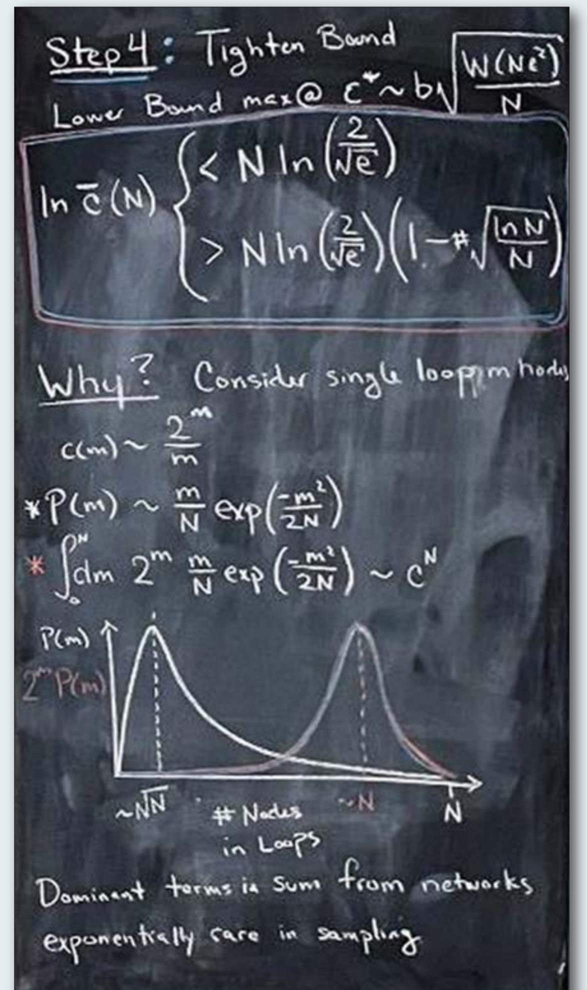
A blackboard, then, is a stage for stand-up theorists. But the process doesn't end there. What follows is like a relay race, according to Forrest Sheldon, a junior fellow at the Institute. "You take it in turns. One of you has started writing out a problem. But at a certain point, the other one grabs hold of the chalk, like a baton."

Socrates believed the way to do philosophy was by dialogue. Two people proceed by question-and-answer, with an exchange of contradiction and confirmation. "When we're battling it out at the blackboard, it's the same thing," says Fink. "The difference is that we can actually see the argument that we're having, chalked up on the board."

When the race is run, there still remains a last part of the process, says Alisa Sedunova, a visiting researcher at the Institute. "The next morning, when you come back in, the work you did yesterday is still up on the board. You see it every time you walk past. Until, one day, you see something that you didn't see before."

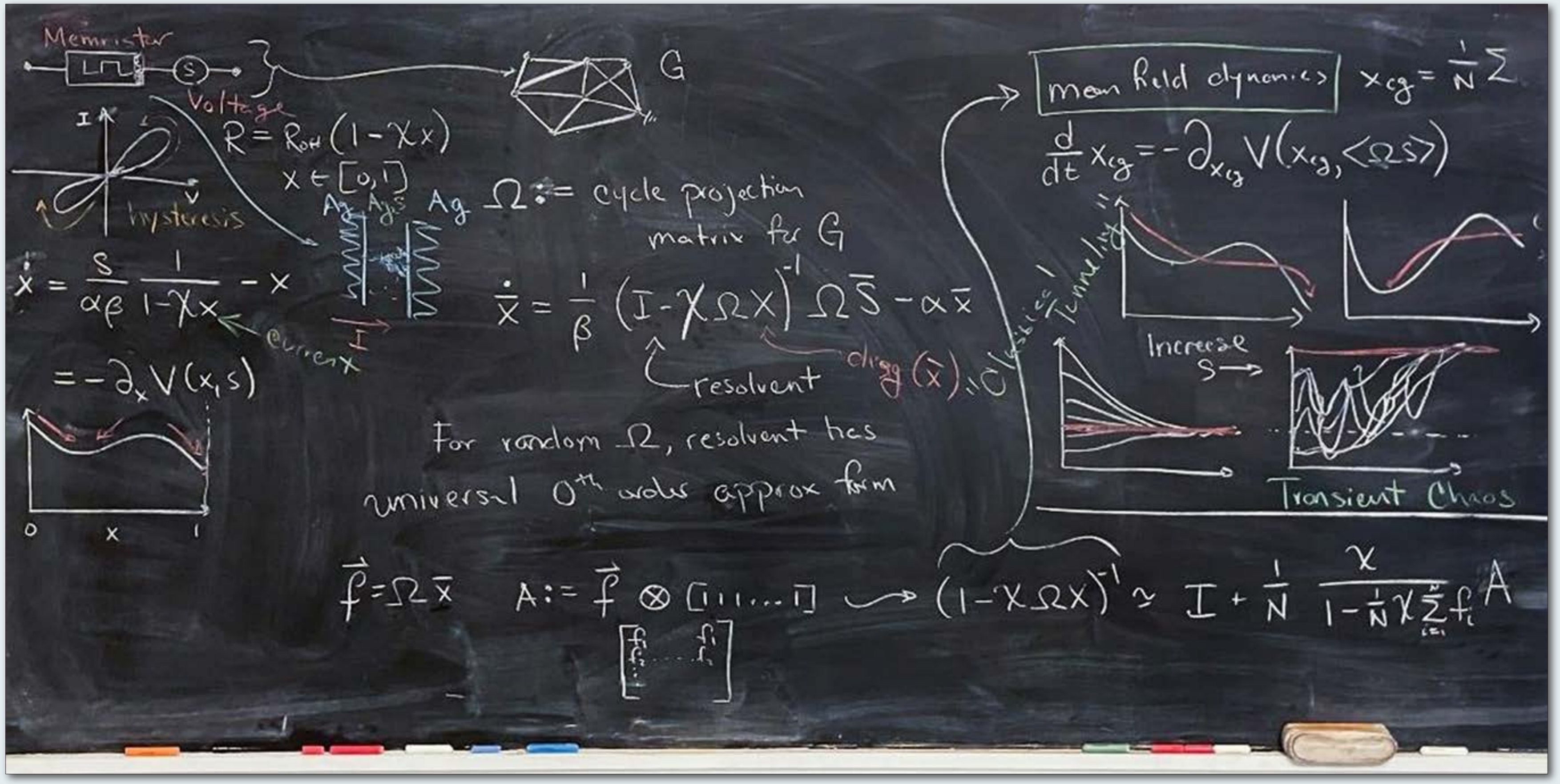
A blackboard skeptic might say that there's no absolute reason why these three stages—the writing, the relay, and the rethink—can only take place on a blackboard. Nevertheless, in practice, most scientists are opposed to digital equivalents such as the Notability app, which allows you to draw on a touchscreen, while sharing your work with colleagues who have the same app. "With blackboards, there's no subtle stress of 'will this work, or will I lose it, or will the server go down?'" speculates Read. "It's a bubble of security that lets the brain think clearly." Partly, too, he suggests, it's because today's screens can be weapons of mass distraction. "You can check your emails, you can look at social media. The limitation of a blackboard is a strength because it forces you to think. It's a very pure medium in that sense."

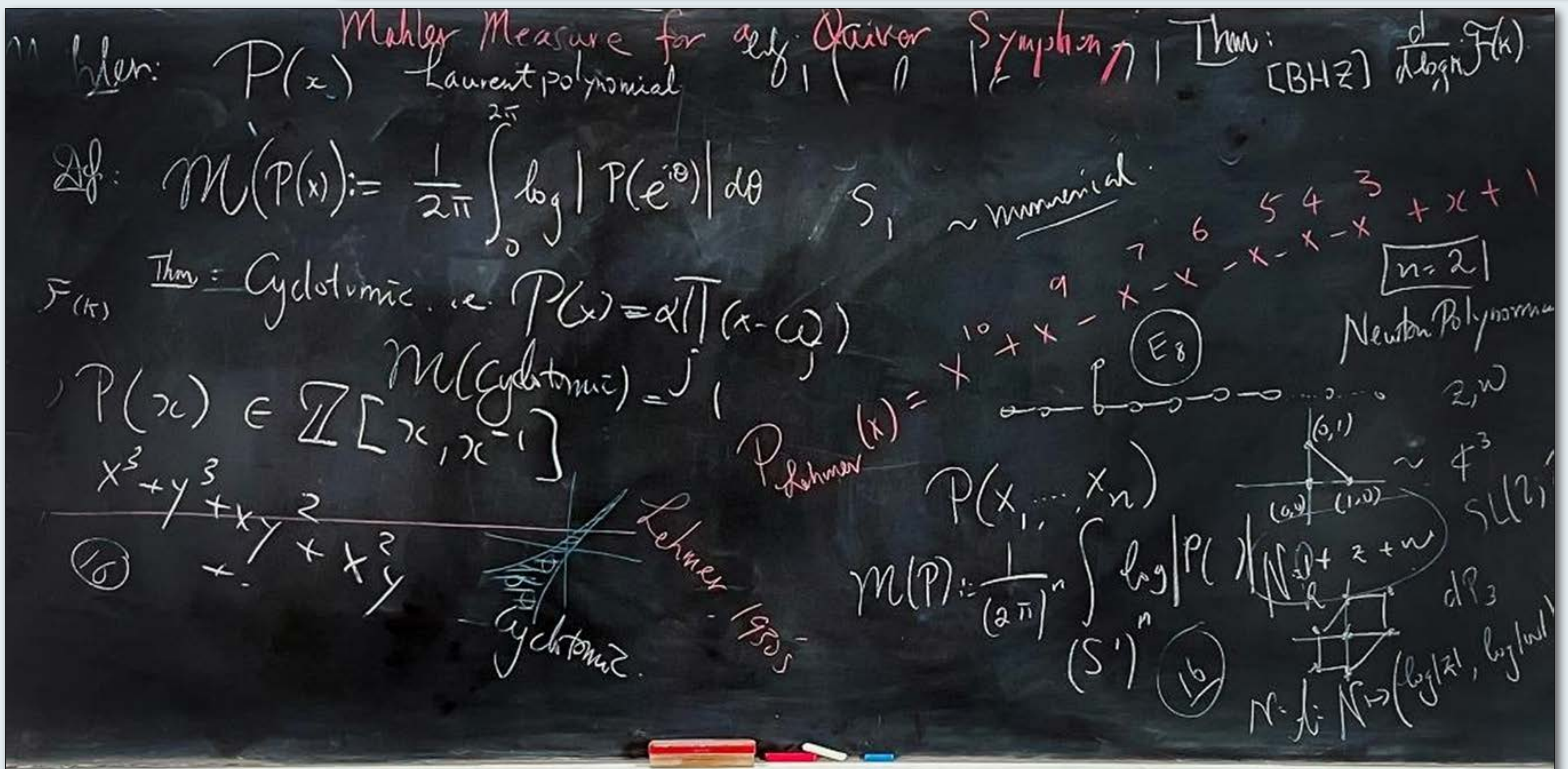
On some level, theorists at a blackboard resemble magicians, philosophers, and athletes. They also have something in common with artists, producing intellectual artworks that seem designed for Instagram feeds. As you walk through the London Institute's exhibition of blackboards, you're struck by their austere beauty.



THE KAUFFMAN MODEL Pictured here (and on page 40) is the Kauffman model, which researchers use to model algorithms that mimic aspects of natural selection. It highlights a feature of biological systems called criticality, a precarious yet versatile state.

MEMRISTOR CIRCUITS
Memristors can be incorporated into electronic circuits and have memory-like properties that allow them to change their resistance based on the amount of charge that has flowed through it in the past. They're used in various applications, like neuromorphic computing, inspired by the structure of the brain.





MAHLER MEASURE
The Mahler measure is a mathematical concept used in number theory and algebraic geometry. Researchers have proposed using it in a branch of theoretical physics called toric gauge theory, which relies on concepts from quantum field theory, a framework in which the universe's truly elementary entities are fields that fill all space.

Blackboards are the best tool for getting unstuck.

If theorists are artists, their chalk is the medium for rough drafts rather than finished products, says He. "The point of chalk is that it's easy to rub out. Theorists are always making mistakes. If they're not making mistakes, it means they're not trying hard enough." As for Fink, he loves the fact that, after the eraser has been used, some trace usually remains of what was written there before. "You can see where they went right, but you can also see where they went wrong."

A recent history of note-making, *The Notebook* by Roland Allen, argues that the paper notebook is more than a tool for thinking. It's an extension of the mind. What the notebook is for words, the blackboard is for equations. So when scientists collaborate in chalk, it's the creative synthesis of two mathematical minds.

For a final word, we talk to Christie Marr, the executive director of the Academy for the Mathematical Sciences, which is currently being set up in the U.K. She sums up the collaborative art of the blackboard. "When you look at it, you can see what kind of dialogue took place there. Whether it was pedagogical. Whether they had it already mapped out. Or you might see three or four hands operating at the same time. Different colors. Smears. Crossings-out. Wrong turns. U-turns and moments of sudden clarity. The end result is a whole conversation that happened in chalk. That's a beautiful thing."

THEO ZENOU is a historian.

THOMAS W. HODGKINSON is a science writer at the London Institute.

Who Controls Your Thoughts?

Our minds are being coerced in covert ways

BY KATHERINE HARMON COURAGE

ZAIE / SHUTTERSTOCK

IN 2017, SIMON MCCARTHY-JONES wrote an article about schizophrenia for *The Conversation*. The piece, he jokes, got read by more than two people, which, as an academic—he's an associate professor of clinical psychology at Trinity College Dublin—was a thrill. Shortly thereafter, however, he found himself "just gripped by the iron claws of Facebook," looking over and over again to see who had liked his article, who had commented on it. It was "grabbing my attention, making me think, 'Check Facebook! Check Facebook!'" he said in a recent video call from his office in Ireland.

Was his thinking being covertly, coercively controlled by external forces (in this case, a big tech company)? The experience got him wondering just what "free thought" actually was. And so he started wading into the murky waters of the psychological, philosophical, cultural, and legal assumptions about what constitutes thought—and how it could remain truly free.

His intellectual quest has exited his head, as much thought eventually does, and now exists in the form of a new book: *Freethinking: Protecting Freedom of Thought Amidst the New Battle for the Mind*.

We caught up with McCarthy-Jones, who walked us through the history of criminalizing "thought crimes," the physical boundaries of thinking, and how architecture and urban planning are essential for truly free thought.

The subtitle of your book makes me wonder how you would define the “new battle” for our minds—and if you think that war currently has more than one front?

I think there are four fronts in the battle: There are threats from states, threats from corporations, threats from individuals, and then there’s the threat from the law—in the sense that if the right to freedom of thought is defined very narrowly, we can leave a lot of thought unprotected from the threats from a new technology.

This last one is a hard one. We talk a lot about brain-reading devices being on the horizon. Elon Musk’s Neuralink keeps popping into the headlines with the idea that he’s going to create some kind of brain-computer interface that will allow us to have our thoughts directly translated to a computer. But the question is: How realistic is this type of technology—and is it a threat we need to think about now? My concern is that this has the potential to slip into a bit of a moral panic.

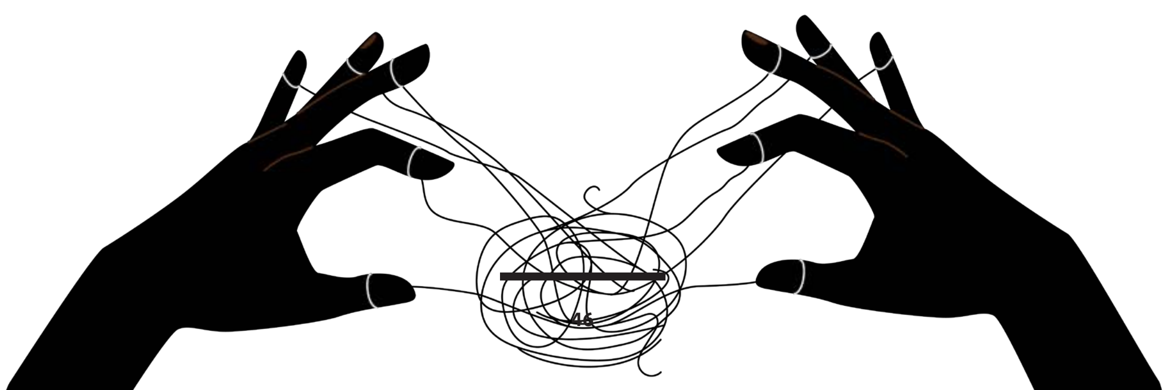
I think what’s maybe a more immediate threat from new technologies is not brain-reading but more what is called behavior-reading. That is, the idea of measuring our observable behavior—what we like on Facebook, what websites we visit, what music we like, etcetera—that from knowing those facts about us, people could impute our mental states and can have a good idea of what it is we’re thinking—and knowing what kinds of buttons they should press to get us to act in a certain way. The combination of that knowledge with AI technologies could be a really huge threat to our autonomy.

In a way, it’s a new technology giving a new perspective to an ancient problem. In ancient Greece, there were concerns about sophists—people who would use argumentation not to reach the truth but to support certain politicians or political ideas. So the concern about sophistic arguments has been around for thousands of years, but now we’re looking at AI as a digital sophist, with a huge power imbalance between what it knows about us and how our minds work—and us as mere mortals.

We might want to say: *No, we’re independent, autonomous thinkers.* But I think we have to recognize that in front of a persuasive AI, we are in deep trouble.

Of course we would like to think that, outside of science fiction, what’s inside our craniums must remain our last, private dominions. But you note that we shouldn’t be lulled into believing this fantasy. How *is* our own free thought being protected?

When I began looking into this—as a mere psychologist and not as a lawyer—there were two things that initially excited and then later terrified me.



The first was that the right to free thought is an absolute right, based on the United Nations’ Universal Declaration of Human Rights. In the United States, it’s as close to an absolute right as there is in the Constitution. And that’s quite exciting because it means that nobody can interfere with your freedom of thought. There are instances where you can limit someone’s speech if it’s defamatory or false advertising or fighting words. But thought is unimpeachable, you can create absolute protection for people’s minds.

But I started to worry about the power of this. Because if it’s not balanced with other social concerns, it can overrule other social interests. For example, you might think that freedom of thought and freedom of speech are natural bedfellows, but the problem is, if you were to claim that a person’s speech was manipulating your thoughts, you could create new limitations on speech in the name of the right to freedom of thought.

And the second thing, which is possibly even more troubling, is the lack of definition of this right. When you look at it closely, there’s nothing there. It’s effectively hollow. It’s bizarre how people through the ages—Jefferson, Voltaire, Chomsky—everyone’s been lauding this right. But in some senses we’ve been so busy lauding it, we haven’t defined it. So even though it appears to be protected, in reality, it’s kind of naked and exposed and very fragile.

The U.N. has tried to define it more recently, but you think they haven’t gone far enough?

In 2021, the U.N. issued a special report that included four pillars of freedom of thought: *Immunity* is the idea you can’t be punished for your thoughts. *Integrity* is the idea that you can’t manipulate other people’s thoughts. *Privacy* is the idea that you have a right for your thoughts to be kept private. And *fertility* is the sense that the state has a duty to create environments for its citizens for freedom of thought.

But there are still these lurking, fundamental questions, just beneath the ice. Questions such as: What should count as *thought*? And what makes thought *free*? How you answer those questions is going to have profound consequences for the extent to which you are actually protecting thought—or how much thought you are leaving vulnerable and unprotected.

OPEN MIND Neuropsychologist Simon McCarthy-Jones proposes that thought is always spilling outside of our craniums—whether in the form of a written to-do list or a brainstorming session with a friend—so laws protecting free thought must also consider these important, less internal types of cogitating.

COURTESY OF SIMON MCCARTHY-JONES

Is this in some way also protecting—as Descartes' words, "I think therefore I am," might suggest—our own personhood, or even our autonomous existence?

Yes, I think thought allows us to decouple from the world, and have this kind of private workspace, where we can create plans, intentions, and unlink ourselves from the demands of the environment and be reflective—and control our actions from the inside. So I do think it plays a central role in us being autonomous.

But by talking about Descartes, we are kind of subscribing implicitly to this idea that thought is something that happens *inside* the head. I see a lot of legal writing on this, where people talk about protecting the inner world, what they call the *forum internum*.

It seems to me that can't be all that we protect. I think a right to freedom of thought that just protects the inner world would abandon more than it would save—because we do a lot of our thinking externally, outside of our heads. As philosophers, technologists, and psychologists would say, there's this important kind of external thought that we need to protect: We count on our fingers, we make shopping lists, we think with technology (like with a Google search), we think with each other through speech.

To let others think for us is to let others live for us.

And that's what you refer to as thought-speech?

Yes, this—although it takes the form of speech—is actually us thinking with others. As E.M. Forster talks about: "How do I know what I think until I see what I say?" And when we speak with others, it's quite possible we're often just *thinking* with others.

There are a bunch of psychology studies showing that, in the right conditions, we're more likely to get closer to truth when we think together as a group, rather than as individuals. Psychology research also suggests that in order to have the best chance of getting closest to a truth, you need to have a group of people with a diverse range of ideas in a room. So it's about creating those spaces. During the Enlightenment, you had the coffee shops across Europe, where you would have space for these kinds of debates—though obviously they weren't terribly inclusive spaces that could bring a diversity of opinions. The question now is: How can you get that diversity of views?

Obviously, we now have online spaces. But unless you're rich or reckless—or a combination of both—it's very difficult to think out loud in those spaces. And if we don't make people feel safe in those spaces, they don't feel comfortable to raise their voices, and you can't get closer to truth.

The idea of protecting this sort of thinking eventually led you to … urban planning?

One of my colleagues from Brazil and I were talking at a conference, and he was telling me about how the design of their capital city, Brasília, was intentionally put together by planners to try to avoid street corners—because street corners were places where people would be able to assemble and potentially think things together, which could be threatening to the ruling regime. So city planning can have an important effect upon the public's ability to think together.

It's also thinking about what kind of things promote free speech. So it's also biophilic design, the idea that being able to walk in green spaces is conducive to thought. Or the things that might help us design our libraries—which in the past would have been dark, dusty spaces—with more light and spaces for breakout conversations. So it's designing buildings and spaces to promote thinking together.

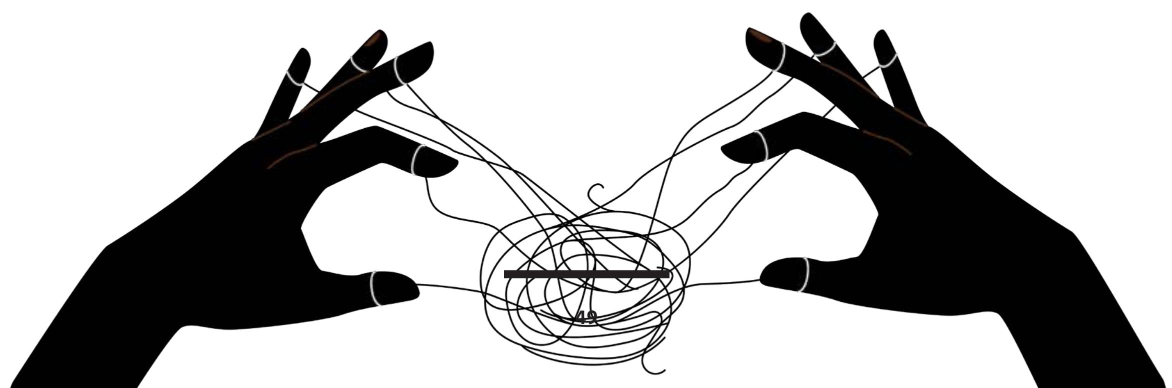
If we sacrifice that ability to think, to what extent are we still human?

We also now, of course, live in a digital world that might not be so conducive to this sort of free thinking, right? The U.N. notes that we should have the right to unmanipulated thought. But we've all had the experience of our own focused attention being taken from us. Nevermind strange ideas like QAnon conspiracy theories being pushed out across the internet. Is there a way out? Or are we already failing?

There is a way to design tech products to—instead of pushing us, through algorithms, in a direction we're already rowing in—a default mode of more "free-thought" options, giving you a more diverse range of opinions. This would help with the problem Donald Rumsfeld talked about—"the unknown unknowns," the things we don't even know we don't know.

It might also help counter what some call "legacy beliefs"—ideas we've acquired at some point but we've never really thought about them. To take a fairly heavy example, you might point to democracy, a concept which I think many of us would take as being an unblemished good. But have we reached that belief by ourselves? Have we ever really *heard* the arguments against it, in order to be swayed out of believing in the benefits of democracy or to help us to really see why we believe in democracy?

Or as a more trivial example, which surprised me: I'd always believed that eating carrots helped you see better in the dark. Obviously carrots have beta carotene, which if you're severely deficient can improve your vision. But during World War II, the British were making radar but didn't want the Germans to know. So they had to come up with a cover story as to why these British pilots were shooting down all of these German planes in the dark. The cover story they came up with was that carrots were being eaten in vast quantities by the British pilots. And that belief just got into the culture. So how can we even find out what things we've been believing for bad reasons?



One can't talk about free thought without bringing up George Orwell's 1949 book, *Nineteen Eighty-Four*. And as you point out, even decades before that—in the 1920s and '30s—in real life, Japan's ruling government had laws that criminalized "thought crimes" to try to stifle dissent. Is there ever a situation in which free thought *should* be questioned, say, as you mentioned before, if it's being abused to stop free speech?
That's one of the controversial areas—whether there is ever any rationale for limiting thought. At the moment, it's an absolute right. And we have a kind of Orwellian knee-jerk reaction to the concept of "thought crimes."

But the philosopher Sam Harris has talked about the possibility of, with the help of reliable brain-reading devices that can detect lies, creating "zones of obligatory candor." For example, in a courtroom, you might be mandated to wear this technology to detect if you were telling lies. On the one hand, this would be a gratuitous violation of freedom of thought. But would society say that's okay in that space?

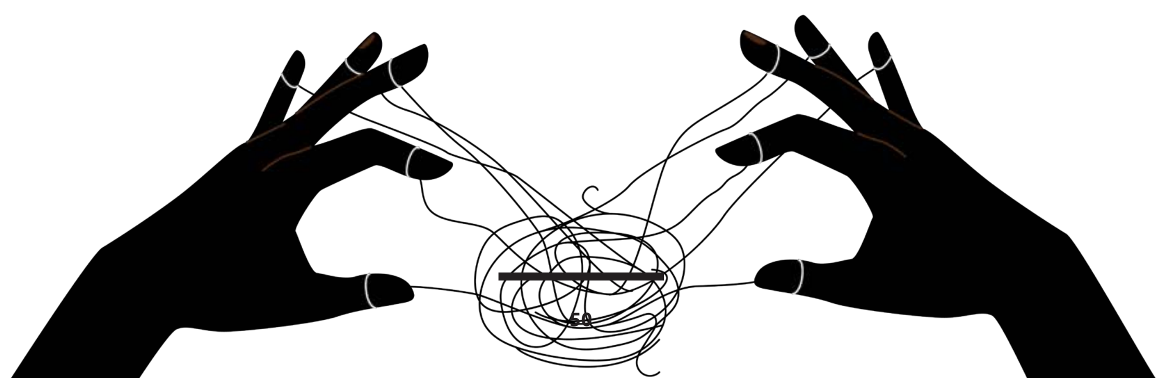
I loved the line from your book: "To let others think for us is to let others live for us." Is that a sort of distillation of the issue for you?
That's what makes us unique as a species. We have the ability to think things through. We've lost our sharp teeth and our claws. But what we've been given to survive in this world is thinking, and that's a large part of what contributes to making us human. If we sacrifice that ability to think, and give that away, then, to what extent are we still human?

People would prefer to give themselves an electric shock than sit quietly with their thoughts.

At the end of the day, though, we aren't actually often drawn *toward* thinking, right? We evolved to conserve energy, and cogitating takes a lot of effort. In fact, you mention a series of studies that found people would prefer to give themselves an electric shock than sit quietly for 6-15 minutes alone with their thoughts. Was that surprising to you—or not so much, as a psychologist?
There's a quote by Daniel Kahneman, the Nobel laureate, who said: "Human beings are to independent thinking as cats are to swimming. They can do it, but they prefer not to."

There are certainly times in my own life where I just don't want to think! And technology makes that easy. For example, YouTube gives us access to a pile of information. And you might think that's going to be helpful for thinking. But do we sometimes use YouTube as, like, a digital benzo, in the sense that we use it to calm our anxiety?

In the old days—old days for us anyway—when you were doing the washing up or mowing the lawn, you'd have time to think. And these days,



we increasingly seem to be accomplishing these tasks with headphones on, with YouTube and podcasts. So are these inputs helping us think? Or are we stopping ourselves thinking by importing other people's thoughts, every hour of the day?

The question becomes: How do we rediscover the joy of thinking? How do we enjoy the *effort* of thinking? Because if we don't really *want* to think again, there's no point in setting up a society that's going to make us do something we don't want to do, right?

What changes have you made in your life to help protect your ability to think more freely?
The first thing I did was to get off all forms of social media. That could, arguably, be an overreaction! I'm well aware Twitter can be a fantastic source of new ideas. But there's a balance to be struck between the extent to which it grabs your attention and draws you away from your own goals. For me, it did more harm than good.

I also think it's quite easy to point the finger at social media and say it was to blame for my attention being pulled away. But we also need to look at who's behind the pointing finger. It may be our own vanity or vainglory or pride that draws us into these social media "likes," where we keep looking for mentions of ourselves. So I think that rather than placing the blame entirely on the shoulders of social media, we maybe also need to examine our own motives and where we're trying to get our own self esteem—and try to manage ourselves more effectively.

The other thing I did was add other types of thinking. As an academic, there's a temptation to lock yourself in a room with a paper or a book and feel that's the best way to progress. But when I saw all the research showing just how valuable thinking with others was and the extent to which our thinking is improved by talking to others, it has forced me—as kind of an introverted person—to try to engage more with other people in different forms of conversations, in spaces that are conducive to free thought—spaces where you're talking to people who you trust, in a safe environment, where you can challenge your own ideas with a diverse range of opinions.

And there is quite a lot of research linking thinking with walking—especially in nature. So I've tried to actively do more thinking on the move, do more walking. And of course in doing so, I'm walking in the footsteps of many philosophers and psychologists.

And walking without podcasts or music.
Yes, leaving the earbuds at home.

KATHERINE HARMON COURAGE is the deputy editor at *Nautilus*.

NASA / CXC / U. WISCONSIN / S. HEINZ

The Echoes of Light

What astronomers see in the light bouncing across the universe

BY LIZ KRUESI

TWENTY YEARS AGO, Andrea Tiengo was a junior scientist watching data stream in from a distant space telescope. He was keeping tabs on routine waves of cosmic X-rays washing over the orbiting, bus-size contraption, relayed to his computer on Earth.

One December afternoon, a peculiar X-ray signal came in. "I saw something like fog, or something blurry, around the point source," Tiengo says. This one looked different, but it looked *so* different from any other X-ray observation he had seen that he thought it could be a problem with the hardware. It was getting late in the day, and Tiengo decided to go home and wait to address the problem in the morning. That, he says, "was a big mistake."

By the next day, the glow was no longer visible to the telescope—and other researchers, instead of him, had made a big discovery. That fog-like signal was the first rings of X-ray "light" from a brilliant gamma-ray burst reflecting off nearby dust. It was an X-ray echo of the blast, an observation no one had ever detected before.

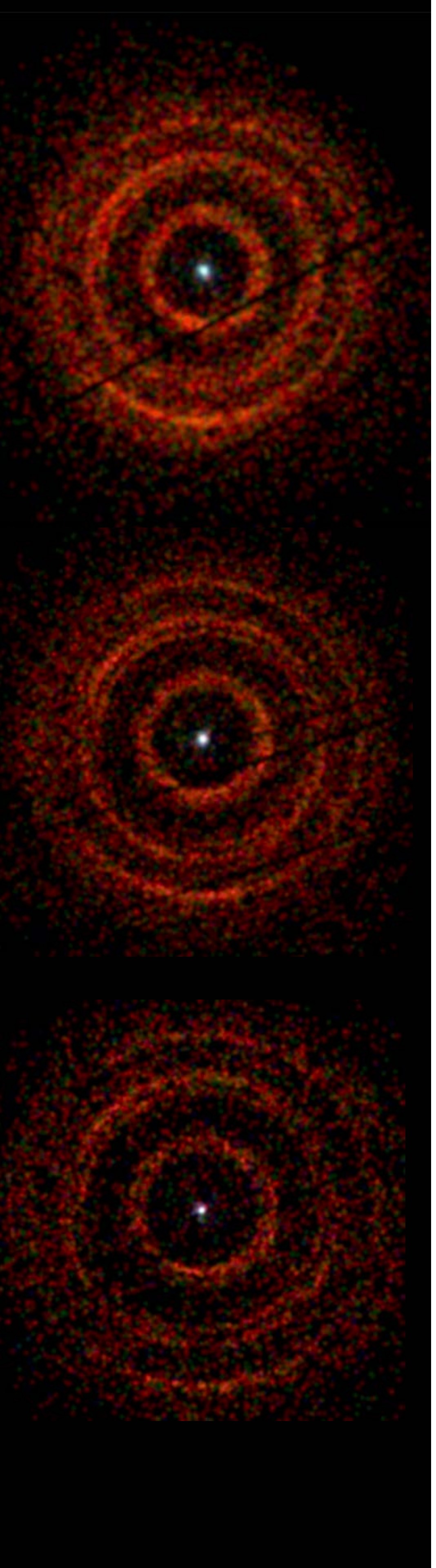
Since that missed opportunity, Tiengo, now an astrophysicist at the Scuola Universitaria Superiore IUSS in Pavia, Italy, has spent the past two decades searching for the echoes of other cosmic blasts and interpreting them. Those reflections, it turns out, are gifts akin to a time machine, a way to watch a replay of the bursting, flaring sources. And from that replay, astronomers can decipher details of the original explosion they couldn't otherwise uncover.

A bit like how bats and other animals use sound bouncing off objects and back to them to understand their surroundings, astronomers can use pings of light energy—not all of which is in the visible range—bouncing off material in the universe. Some types of light, like radio waves, just pass through material instead of scattering off it. But other types, including X-rays and visible light from a star's explosion—or any changing cosmic light source like a brightening star or a burping black hole—bounce off intervening dust on its way to our eyes and telescopes.

That echoed light ends up taking a longer path to Earth, arriving minutes to millenia later than the original burst's signal. The length of the delay depends on how much the light roamed and bounced on its way to Earth. And from these second-hand signals, astronomers can begin to reconstruct the stellar blast, rewind the events that led to it, and map the material that lay between it and us.

Although the study of these distant echoes has risen to the fore over the past 20 years, its history extends much further back.

IN FEBRUARY 1901, astronomers saw a brilliant "new star," or nova, in the sky. This star, Nova Persei, had brightened temporarily after an explosion at its surface. This several-day flash of visible light radiated away from the star and bounced around nearby clouds. Later that same year, observers spied a fog around the star—light echoes.



X-RAYS MARK THE SPOT In July 2015, a satellite-based telescope captured X-ray flares echoing off of dust clouds around an erupting black hole about 8,000 light-years away.

These sorts of events create ideal sources of light echoes for study. And our sky hosts heaps of them. Or has, over the centuries.

In November 1572, it looked like a bright new star had suddenly appeared in the sky. Seen by many and visible to the naked eye, it was described most extensively by Danish astronomer Tycho Brahe—and subsequently dubbed Tycho's supernova. Some time in the next century, light from another supernova, Cassiopeia A arrived on Earth. The original light flashes from the catastrophic explosions of these once-stars have long-since dissipated, but their echoes are now washing over us. They are the radiating landscapes on which Johns Hopkins University astronomer Armin Rest trains his focus. Through them, he says, "We basically can go back in time."

Within these echoes, he has found, lie patterns of imprinted information: missing spectral colors that correspond to specific molecules and elements. This is the same pattern as what the original source released, and so seeing an echo later means astronomers can step back and reconstruct the details of the original event. And because oftentimes, they don't see just one echo but instead see multiple echoes over time, they can watch how the stellar explosion evolved.

With echoes working as sort-of portals to the distant past, Rest and his colleagues have been able to watch a supernova's blast and paint a picture of *how* it exploded. We haven't been able to watch a star explode in real-time, and computer models still struggle to get the details right. So replaying the blast with the delayed echoes lets astronomers peek into the crucial moments.

Even fresh echoes have much to teach us. On Oct. 9, 2022, the brightest gamma-ray burst ever detected showered Earth with its rays. While its original X-ray light blinded most telescopes—making immediate headlines across the globe—the brilliant light energy bounced off nearby dust clouds and gave Tiengo and colleagues echoing rings of that X-ray emission a couple days later. Over the next month, the XMM-Newton satellite he works with captured 20 rings, all surrounding the site of the original blast.

"Each ring," says Tiengo, "is the vehicle of the same emission" and carries the burst's imprint. By studying the spectral imprint in these rings, the astronomers reconstructed the details of the original flash: They could see into the past and watch a burst that couldn't have been observed any other way. From those 20 rings, Tiengo says, they see a hint of something surprising in the explosion, which released more X-rays but with lower energies than expected. Tantalizing clues they and other scientists will continue puzzling over in the quest to better understand how massive stars live—and die.

ANDREW BEARDMORE (UNIV. OF LEICESTER) / NASA / SWIFT

Other groups of astronomers are using light echoes to study some of the most mysterious cosmic monsters in the universe. Shuo Zhang of Michigan State University is piecing together the history of outbursts from the supermassive black hole at the center of our galaxy. This behemoth, Sagittarius A*, or Sgr A* for short, today is quiet compared with the tumultuous beasts at the centers of other galaxies. But light reflections off blobs of material at our galaxy's core imply Sgr A* had a more active and louder past.

Zhang has combined some 20 years of X-ray images from giant clouds of molecular gas, blobs that, she says, "are the perfect recorder to any past outbursts in the galactic center." Such an outburst follows the black hole snacking on a gas stream, an unlucky star, or some other material that came too close to Sgr A*'s strong gravity. Before being ingested, the snack stretches and swirls around the black hole, spiraling at its outskirts. Those tumultuous movements spew heat and X-rays, which hit the molecules in the nearby giant gas clouds. The light gives some of its energy to the gas in the clouds, making them light up. But some of the X-rays aren't absorbed and instead bounce off particles in the cloud, like sunlight bouncing off the rippling surface of a lake. That bouncing light's detour gives it a longer and delayed path to our telescopes. And so, today's telescopes see the delayed light released during our black hole's last swirling snack as echoes, hundreds of years later.

The echoes Zhang and her colleagues have tracked over the years, in addition to other X-ray data from different teams, show our galaxy's central black hole was more active about 200 years ago. The scientists will keep watching as those echoes from the gas clouds continue to evolve over the next several years. They're looking for the echoes to quiet, which will tell them how long the black hole flared.

The echoed light arrives minutes to millenia later than the original burst.

MUCH OF THE SPOTTING of these echoes is still done the old-fashioned way, by humans pouring over surveys, squinting for the faint fog or rings that large cosmic events leave behind.

But that will change over the next several years. "We are soon ushering in this era of time domain surveys," says MIT astrophysicist Erin Kara, describing the new approach that will quickly map the sky and reveal minute changes. Kara, who uses light echoes to study the innermost portions of a black hole's environment, notes that this will be key in finding more radiating echoes in the universe.

Upcoming projects, like the Vera C. Rubin Observatory—scheduled to begin operations in January 2025—and its Legacy Survey of Space and Time will collect scattered light across huge swaths of the sky at once and return to the same view frequently. Complex computer programs will subtract images to look for changes—like brightness variations that could lead to light reflections and foggy light arcs that move from one image to another, indications of echoes. Other future endeavors, such as the China-Europe Einstein Probe, will use a perch above our planet and new technology inspired by lobster eyes to capture an even wider area of the cosmos. With these and others, scientists will step back in time and untangle how these spectacular cosmic events unfolded.

This work takes a broad view. "It's always better to have more photons than less," says Tiengo, especially when you're searching for the faint whispers of flareups from across space—and time.

LIZ KRUESI writes about the stories of the universe from her home base in Colorado, a mile closer to the stars.

The Groundhog Watchers

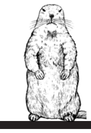
Meet Susan and Joe. Their daily observations of the groundhogs in their yard are making science history.

BY BRANDON KEIM

ONE SPRING MORNING IN 2003, Susan Sam looked out the kitchen window of her home in rural Imlay City, Michigan, and saw a small brown animal on the lawn. Not recognizing the creature, she called over her husband, Joe. He identified it as a groundhog. Having heard stories about their destructiveness, Joe suggested they get rid of it.

Susan, however, was curious. "Why don't we watch for a while?" she suggested. "Because so far, I'm not seeing anything horrible." Joe agreed that they could keep an eye on the groundhog and see what happened. They named her Wilhelmina. Not long afterward, they saw Wilhelmina carry a litter of still-fuzzy babies to a burrow near their sun porch. Two weeks after that, the groundhog family emerged; the Sams, again looking out their window, were enthralled. Twenty years later, they're still watching.

With Joe's help, Susan has chronicled the lives of generations of groundhogs who made a home beside her own. She's become an unlikely champion for creatures often regarded as vermin, killed for sport or because many people reach for a gun—or a trap or dry ice—rather than building a fence or filling in a hole. Their efforts have yielded a uniquely detailed, eye-level portrayal, perhaps even adding to what scientists know about the life history of a species at once widespread yet obscure.



She's seeing them as though she's living with them.

Now, "obscure" might seem an odd term for groundhogs. They're the only animal with an American holiday, and though Groundhog Day is tongue-in-cheek nowadays, it's still celebrated. They're considered common throughout Canada and the eastern United States, where they're capable of dwelling in backyards and in-between spaces of suburban sprawl. Most residents in their range have at least glimpsed a groundhog eating by a roadside.

I learned about the Sams several years ago, after a groundhog's decision to raise her babies in a burrow beside my deck sent me Googling to learn more about them. There was plenty to be found about their biology: *Marmota monax*, a ground squirrel, digs central burrows up to 60 feet long, with separate chambers for nesting and defecation; their body temperature drops to 37 degrees Fahrenheit, and their hearts beat just five times per minute, during hibernation. There was seemingly endless advice on getting rid of them. As for their social lives, though, there was little to be found.

The only detailed descriptions came from the Sams' Woodchuck Wonderland website and books—"woodchuck" is another name for groundhogs—and from Christine Maher, a biologist at the University of Southern Maine whose long-term study of groundhogs at a nature sanctuary described them living in loose-knit, kin-based communities, mostly keeping a day-to-day distance from one another as adults but still sharing territories with familiar individuals.

Her observations dispelled the still-pervasive misperception of groundhogs as solitary, with no social contact outside of mating season and a brief period of maternal care. Yet even Maher's work is hindered by the fact that, as summer progresses and vegetation grows taller, it becomes difficult to see them. The Sams, who keep the area around their house mowed, have no such problem, giving them a front-row seat from spring to fall. And while Susan takes pride in the rigor of her observations and corresponds regularly with researchers, her interest is not narrowly scientific.

"It was like, 'Everybody hates you. But we're not seeing anything horrible here. And we're just going to have to tell your story,'" Susan says of the day when Wilhelmina and her babies gathered by her sun porch. Though Wilhelmina is gone, having last been seen in 2011, the mission continues.

ON THIS JULY MORNING, Susan sits at her kitchen table watching three russet-furred juveniles eat clover in the yard. Between there, the sun room, her studio, and the bedroom, she has a panoramic view of the main territory. Six cameras positioned on tripods, plus three video cameras, allow her to document what happens. "The house is our blind," she tells me on the phone.

The youngsters are the progeny of Winnie and Milo, each of whom arrived the previous year. Except for one juvenile—Limper, so called because of a congenital deformity in his left front paw—Susan hasn't yet been able to discern distinctive markings by which she could recognize them individually. The morning continues quietly, with the groundhogs' perambulations interrupted only by the appearance of a gray squirrel whose unexpected presence briefly scatters them.

After a few hours of observation, Susan puts on a mix of Toto, a rock band best known for their cryptic 1982 hit "Africa." Susan and Joe are superfans. She recounts how, when they had to cancel plans to attend a concert, they asked a friend to deliver a copy of their first book to Joseph Williams, the band's current lead singer. "He sent a very nice email afterward thanking us," she says.

By noon, Susan has taken more than 100 photographs: by her standards, a fairly light day. These are

WOODCHUCK WONDERLAND
A young groundhog surveys the yard around the Sams' home. The birdbath is an especially popular feature. "All these babies and the adults—generations of them—lay underneath that birdbath," says Susan.

PAGES 56 & 59: SUSAN SAM

PATERNAL CARE A male groundhog named Milo play-fighting with a pup. Conventional wisdom holds that male groundhogs are not involved in raising their young, but the Sams have documented what they interpret as evidence of paternal care.

SUSAN SAM

grist for the stories she'll later tell on the website and social media. She hopes that Winnie, who in June carried the babies by mouth from their natal burrow beneath the shed to a summer burrow beneath the barn, will make an appearance. Susan is interested in how she raises her young, especially the deformed Limper.

At this stage in their lives, says Susan, Winnie deposits them in different parts of her territory as they learn to navigate life on their own. Last week, Winnie took two babies to the rock garden while leaving Limper and another sibling down by the shed. When Limper's companion tried to join the others, "she popped him good, disciplined him, and took him back to the shed." Winnie wanted him there for a reason, and the tough-love enforcement was not unusual: Groundhog moms are a no-nonsense bunch. But when it comes to Limper, Winnie is uncommonly patient.

"Winnie treats him differently than she does the other ones. If they start hanging around or whatever, she'll discipline 'em. It's like 'Get away, you've got to to be independent.' With Limper, she doesn't do that," Susan says. "She allows him to follow her around. She doesn't pop him."

I think there's a lot waiting to be seen under our noses.

LYNN OLIVER, A WILDLIFE REHABILITATOR who co-founded Valley Wildlife Care in Middletown, Virginia, says the Sams' observations of groundhog family life have been invaluable to her work. They helped her understand that babies need more activity than she realized, and that they're not necessarily ready to be released at just two months old—an age when they're typically considered independent, but at Woodchuck Wonderland are still being watched by mom.

"She's seeing them as though she's living with them. Which she is, but through her window," Oliver says. "Her stories have filled in gaps for me about how these animals lived before they became orphaned or injured."

Another rehabber who communicates regularly with Susan is Betsy Shank, the executive director of Acorn Acres in Millersville, Pennsylvania. "I think the work they're doing is incredibly important," Shank says. The Sams, she explains, "are the 'average Joe.' They don't have all these grants supporting them. They're sitting there in their home providing valuable information."

Shank brings up how Susan and Joe have observed male groundhogs caring for young. That contradicts the conventional wisdom, which holds that groundhog moms raise their offspring alone while dads remain distant: present in the home territory, but otherwise uninvolved. Over the years, the Sams have documented what they interpreted as paternal behavior—standing guard, play-fighting to help prepare youngsters for future encounters—in no fewer than six groundhog dads. Among them is Milo, who the summer prior raised a litter by himself after their mother disappeared.

"Dad came in and finished raising those pups, which is unheard of! We all sat there with our mouths hanging open saying, 'Oh my gosh,' " Shank says. Susan is especially proud of these observations, which are described in a self-published paper entitled "Backyard observations of the behavior and role of the male woodchuck (*Marmota monax*)." "How much of this goes on where people can't see it?" says Susan.

I asked Christine Maher, the biologist who studies groundhogs in Maine, for her thoughts. She and Susan have corresponded, and "I appreciate their commitment and their observations," she says. Still, Maher isn't convinced about the fatherly attentions. "I suspect that much of the behavior can be explained in a sexual or reproductive context," she says. Rather than providing care, dads might be courting potential future mates. Perhaps some are not dads at all, with paternity actually belonging to some unidentified rival. "I think their results can be interpreted in other ways," says Maher.

Yet Dan Blumstein, an ethologist at the University of California, Los Angeles who studies sociality in ground squirrels and is also in contact with Susan, is more open to the possibility. "These are certainly more than anecdotes," Blumstein told me of the Sams' observations. "They're not doing statistical analyses—but they're

THE GROUNDHOG WATCHERS
Susan and Joseph Sam shortly before their 50th wedding anniversary. "I basically do whatever Susie needs me to do," Joe says. "She's the driving force. They always say that behind every man you find a great woman. In this case, behind a great woman you might find a good man."

KATE BUTTERFIELD HALBADEL

explaining things they're seeing that haven't necessarily been recognized as common, or even recognized in the published literature."

Blumstein suggests other researchers might pursue those observations. "If anything, their role is to say 'Hey, these guys need more study,' " he says. And while the parenting habits of groundhogs may seem an esoteric subject, they represent something more transcendent: that much remains to be learned about even the common, everyday animals who live all around us, and regular people can help illuminate it. "I think there's a lot waiting to be seen under our noses," says Blumstein.

EARLY IN THE AFTERNOON, Susan steps away for a while and Joe, who throughout the day alerts his wife when groundhogs are seen from other rooms, picks up the phone. He chuckles about his early sentiments. Back when they met Wilhelmina, he'd just retired from his work as a machine repairman at the Ford Motor Company; like Susan he'd grown up in Detroit and knew groundhogs only by their reputation.

"I was most apprehensive," he says. "I had the typical knowledge that most people get of woodchucks. They're going to dig holes, ruin your lawn, eat your vegetables and your flowers, and cause your buildings to fall down." But it was important to him that he support her burgeoning interest, and "pretty soon I found out that the things I believed to be true were not."

Of course, that doesn't mean groundhogs are always perfect neighbors. They *do* eat vegetables and flowers—though people often blame them for the snacking of other critters—and their burrows cause problems when dug near a foundation, in time allowing moisture to seep in and weaken the structure. A peaceful coexistence takes effort, and the task of fencing off flowerbeds that he and Susan want to protect falls to Joe, as does filling entrances to burrows dug in inconvenient places. They're careful to do this only when the burrows are not in use. If that means waiting for a season, it's not a big deal.

"I think that all creatures have a right to life," he tells me. "Granted, because I was a warrior in Vietnam"—he fought as a member of the U.S. Marine Corps—"I conducted myself in ways there that aren't necessarily conducive to that. But that was war. So as a result, I've done what I could to ensure that life on our property has a chance to thrive."

Pretty soon I found out that the things I believed to be true were not.

For him and Susan, setting this example is as important as their observations of groundhog life. Woodchuck Wonderland isn't just about knowledge. It's about values and how we relate to the animals around us.

In Michigan as well as most places, groundhogs can be hunted year-round without limit on the number killed. YouTube abounds with videos of people using them for target practice. Total mortality is difficult to estimate, as not all states bother to count; in neighboring Illinois, roughly 10,000 groundhogs are killed each year by hunters, and in Pennsylvania, cradle of Groundhog Day and home to Punxsutawney Phil, the annual toll is around 800,000.

What people do in their backyards, however, may have an even greater impact. Restrictions on killing so-called nuisance animals are typically minimal. In Michigan, property owners can kill a groundhog at any time for being "physically present where it could imminently cause damage," a proviso that essentially makes their presence near human habitation a cause for elimination. Often people have no enmity toward them but are simply concerned for their property; they might even be kindhearted and relocate groundhogs—but being exiled in an unfamiliar place can be a death sentence, too. The fate of a great many animals, and whether they thrive in a human-dominated world or scrabble in its margins, is ultimately a matter of personal conscience and the willingness to do a little work.

As the day's shadows lengthen, Winnie finally makes an appearance. Susan delightedly describes Limper's reaction. "It's like, 'I'm so happy! I'm so happy!' He just bounces around the yard, following wherever she goes," she says. Limper follows her to the edge of the front yard. It's the farthest he's ever been from his burrow and a foreshadowing of how quickly he'll need to grow up.

With his deformed paw, life will be hard for Limper. The weeks between now and autumn are a race to pack on as much weight as possible for the winter's long hibernation. Susan hopes Winnie will allow Limper to stay nearby rather than venturing out into the wider, less tolerant world. Later in the summer, she and Joe plan to remove the fence around their marigolds so as to give him some extra nourishment.

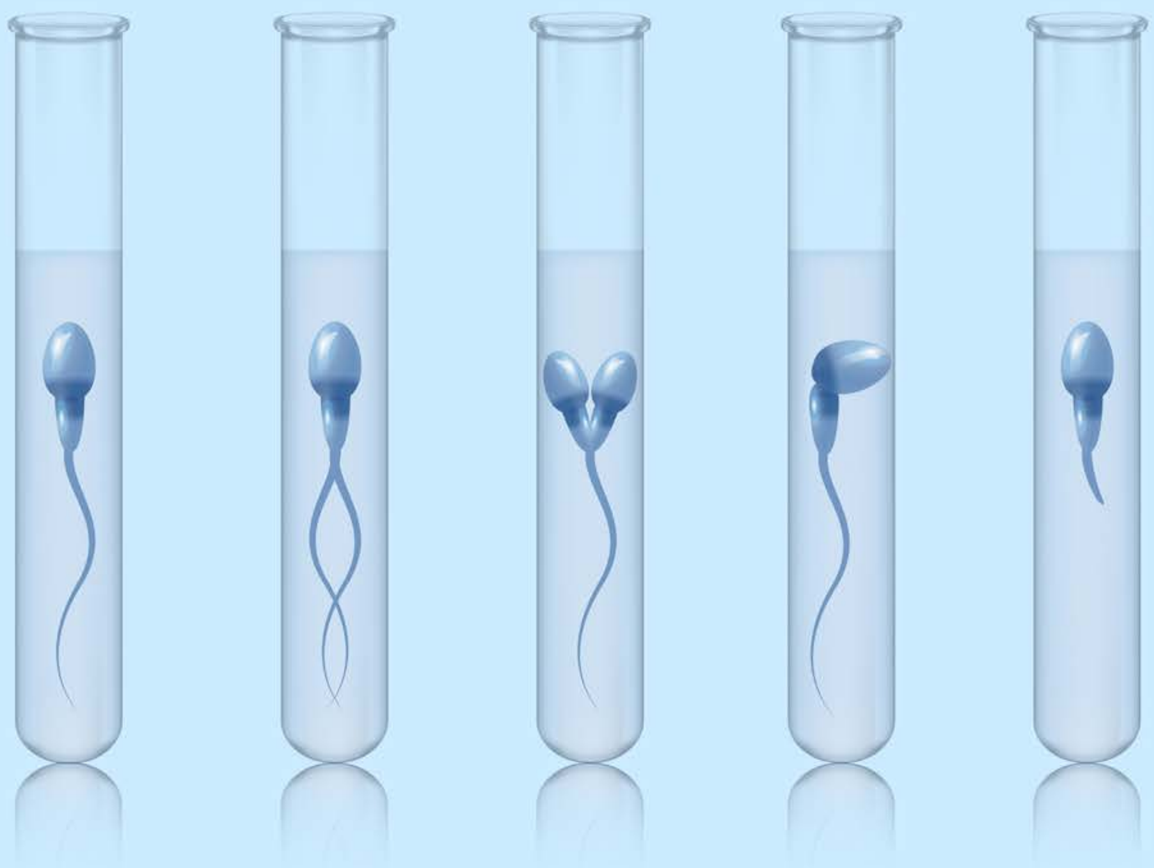
"There's so much misinformation and misunderstanding about them. We're hoping to bring some tolerance," Susan says. "So what if you lose a few flowers?"

BRANDON KEIM is a freelance journalist and contributing editor at *Nautilus*. His new book is *Meet the Neighbors*, a book about animal personhood and nature.

What You Don't Know About Sperm

A remarkable tale of evolution

BY DAVID P. BARASH



VADI FUOCO / SHUTTERSTOCK

SPERM DON'T GET MUCH RESPECT. They're little more than a bare-bones package of DNA outfitted with a lashing tail. And they're produced in such vast numbers that no single pollywog counts for very much. We all know about their co-starring role in reproduction. But as a 2023 *Nature* paper underscores, sperm represent some of the most extraordinary and counterintuitive processes of evolution—which got us all here in the first place. So maybe it's time we get to know sperm better.

To begin with, spermatozoa not only embody the reproductive prospects of males who make them, they have remarkable agency in themselves. Evolutionary biologists have long known that among many species, males compete with other males, the ultimate fitness payoff being that winners will get to project their genes (via their sperm) to the next generation. But competition is also being waged *inside* male bodies. Sperm battle to fertilize a female's egg, but they continue to battle even after copulation, perhaps for their own evolutionary payoff.

What's surprising about the new *Nature* study is that it shows sperm also cooperate with each other. Human semen is of low viscosity compared to much of the female reproductive tract. When the hard-working little swimmers encounter the thicker vaginal mucus, their path is slowed. So the sperm often join together at their heads, which gives them greater swimming speed (up to 50 percent faster) than if they were to carry on individually.

What's more, human sperm with higher DNA integrity (less fragmentation) are more likely to associate together, practicing their strategy of all-for-one, one-for-all. When the local viscosity diminishes, they disband their Musketeer-like cooperativeness, reverting to each pollywog for himself. Interestingly, the *Nature* researchers also simulated cases in which a female copulates with more than one male. They found that related sperm—produced by the same male—preferentially associate together, gaining an advantage over their unrelated non-brethren, who are slowed down when they form analogous groups.

When sperm disband their cooperativeness, it's each pollywog for himself.

This collaboration of related sperm is biologically consistent with the evolutionary phenomenon of kin selection, whereby individuals (whether bodies or gametes) are selected to benefit others that carry shared genes. Those individuals who have genes in common are called "relatives." When they behave in this way—aiding other bodies with whom they share genes—we call the behavior "altruism," although it's really a matter of genes behaving for their own benefit and using bodies to achieve this end.

This recent evidence of human sperm cooperation is stunningly counterintuitive, because in most respects, competition is the name of the evolutionary game, especially when unrelated individual bodies struggle to be reproductively successful. And this competition is especially intense among males.

Until recently, biologists have assumed that nearly all this reproductive struggle takes place among individual males. Turning the focus on gametes has revealed a new world of evolutionary strategies, in which individual males struggle with each other, not just via their bodies, but also via their sperm. Essentially, the behavior of sperm is analogous to the behavior of individual males, with the same forces of evolution playing out on both levels. The key is that males realize their success by making their sperm successful, and much of that success depends not just on their bodies but on the sperm themselves.

Here, testicles have a tale to tell. Both chimps and bonobos have enormous testicles. In these species, the females end up mating with more than one male. From the male perspective, the more sperm you have in the game, the more likely you are to win. Even in cases such as bonobos, where males don't compete very vigorously, there's still plenty of male–male competition, much of it taking place within the reproductive tract of females.

By contrast, among gorillas, male-male competition is *pre*-copulatory, occurring via bodies rather than sperm. Dominant harem-holding silverback males have already achieved their status by physically defeating and intimidating other males. They don't need to produce lots of sperm, because no other male will likely copulate with their females; hence, for all their great size and strength, male gorillas have comparatively tiny testicles.

Human testis size, relative to body weight, is closer to that of gorillas than to chimps or bonobos. In harem-forming gorillas, testes are about 0.02 percent of body weight, and their ejaculates are relatively dilute, with roughly 5 million sperm per squirt. No need to make a lot of sperm, or a highly concentrated ejaculate, if you're the only guy likely to inseminate a female. By contrast, chimpanzees have testes that are proportionally 15 times larger (0.3 percent of body weight), and their ejaculate is 14 times more sperm rich (60 million pollywogs at a time). Human testes are on average 0.06 percent of body weight and sperm concentration is about 25 million per ejaculate. This pattern is consistent with data on the average number of male sex partners for females per birth: gorillas, one partner per birth; human beings, 1.1; baboons, 8; bonobos, 9; and common chimps, 13.

Not only do men have relatively small testicles, they also have reduced Sertoli cell mass. These cells help nourish the developing sperm and are sometimes called "nurse" cells. With less sperm competition, there's less need for the little swimmers to be bulked up. In addition, men possess comparatively small sperm reservoirs, of the sort expected if sperm were to be ejaculated perhaps every few days rather than many times per day, as in multimale, multifemale troops such as chimps and bonobos. Incidentally, there are some species in which males produce substantially fewer sperm per ejaculation. Among some kinds of seahorses, for example, sperm are numbered by the dozen rather than by the hundreds of million. This makes sense because their females deposit eggs within the males' brood pouch, where they are fertilized without risk of intrusion by other males and their sperm.

IT IS ONE THING to note how males often use their sperm to compete with that of other males, quite another to explore whether sperm compete directly with each other, even within the ejaculate of the same male. But in fact there is a degree of mano-a-mano competition, with tiny spermatic gladiators carrying on evolutionary battles against other suitors, albeit those with the same forefather.

To be sure, individual sperm are closely related insofar as they were produced by the same male; but they are also genetically distinct from each other. Following spermatogenesis, each sperm carries its own random assortment of one-half its producer's genes, so they are nearly always genetically distinct from each other. As a result, individual sperm struggle with each other within the micro-arena of a female's reproductive tract. Success of any given sperm will be determined by its ability to outperform its … shall we call them brothers?

PAPA BRAVO / SHUTTERSTOCK

BIG AND SMALL Dominant silverback male gorillas don't need to produce lots of sperm because no other male will likely copulate with their females. So for all their great size and strength, they have small testicles.

In many species, males will guard "their" females after copulation, to deter other males from mating with the female in question. Not uncommonly, ejaculates will congeal within the female reproductive tract, forming copulatory plugs that prevent semen from leaking out while also preventing other males from getting in. Some insects carry this tactic to extremes. In certain bee species, the male's body literally explodes after copulation, due to a sudden increase in intra-abdominal pressure, which embeds part of the now-deceased male's body into the female's genital tract, preventing other males from copulating with the just-fertilized female. Among many mammals, including chimps, females have also evolved post-copulatory counter strategies in which they sometimes remove those plugs, making themselves available for subsequent mating and fertilization. Interestingly, this hasn't been observed among orangutans, in which females copulate almost exclusively with just one male, and among which copulatory plugs aren't even produced.

Although sperm competition theory is focused on strategies of male-male competition, females are not without agency in this regard, using tactics that go beyond removing or dissolving copulatory plugs. Sexual selection theory is replete with cases of female choice, first described by Charles Darwin. Eggs, unlike their spermatic counterparts, are relatively immobile: To our knowledge, there is no egg-egg competition. But there is strong evidence that females set the stage for what is known as "cryptic female choice." Rather than orchestrate their anatomy and physiology to facilitate fertilization—as a naïve evolutionary perspective would suggest—females often make this essential evolutionary process rather difficult; for example, by sequestering their eggs on the far side of twisty, difficult-to-access tubes, selecting for sperm that are especially vigorous. And perhaps also favoring those with a tendency to cooperate when traversing a high viscosity medium.

Ecologists distinguish between two fundamental mechanisms of competition: scramble competition and contest competition. In scrambles, sheer numbers are key. Imagine an Easter egg hunt in which the winner accumulates (or fertilizes) the most eggs. In contest competition, participants would first compete with each other, independent of the actual egg hunt, after which the winner gets most of the eggs. Given that sperm are produced in such vast numbers, it is clear that simple scrambles are an important way that sperm competition takes place. The question arises, however, whether contest competition also occurs among sperm.

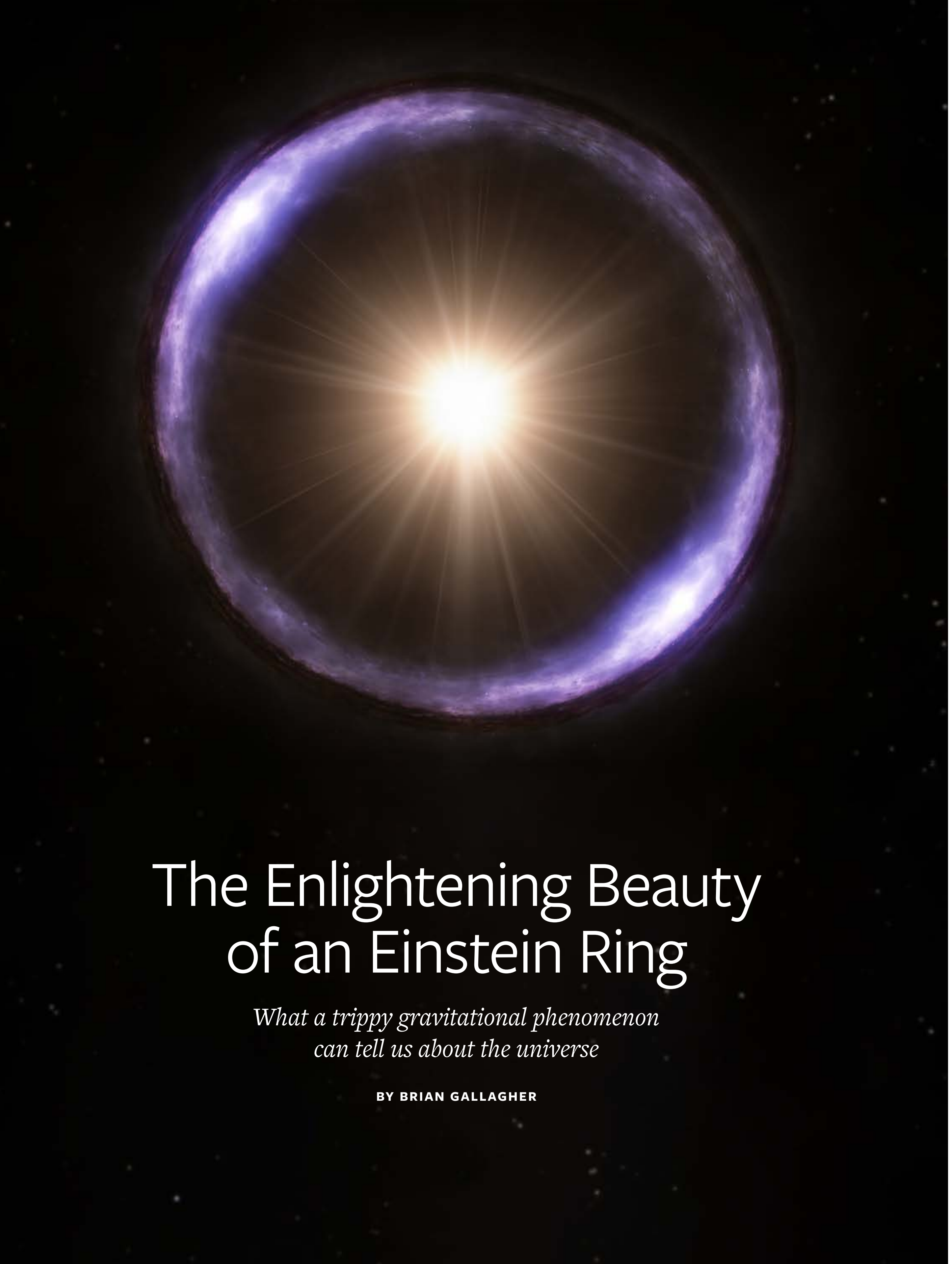
About one-fifth of mammalian (including human) sperm are typically abnormal, containing no heads, two heads, two or more tails, oddly misshapen or malfunctioning tails, and so forth. As a result, they can't achieve their traditional function, namely fertilizing an egg. Abnormal sperm have generally been seen as the result of simple biological blundering, whereby errors are unavoidable, perhaps especially when the end products are made so rapidly and in such great numbers.

Some biologists in the 1980s hypothesized that aberrant sperm aren't failures but "kamikaze" sperm. The idea is that these might be produced by males as part of a competitive strategy whereby their function isn't fertilization but rather sacrificing themselves to entangle and otherwise disable other sperm. Alternatively, these supposedly self-sacrificing sperm could also contribute to the formation of those copulatory plugs. Alas, this intriguing notion is not supported by current theory or data. It appears that although male bodies compete largely via contest competition, sperm do it mostly by scrambling. And the occasional cooperation.

The more we study the living world, the more diverse, complex, and downright fascinating are the maneuvers by which natural selection does its work. I suspect most of us never realized that goes for sperm, too.

Human testis size is closer to that of gorillas than to chimps or bonobos.

DAVID P. BARASH is an evolutionary biologist and emeritus professor of psychology at the University of Washington. His most recent book is *Oops! The Worst Blunders Of All Time, from Pandora's Box to Putin's War.*



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The Enlightening Beauty of an Einstein Ring

What a trippy gravitational phenomenon can tell us about the universe

BY BRIAN GALLAGHER

NOT LONG AGO, Pieter van Dokkum received a delightful invitation. Would he like to have a look at new images of the universe no one has ever seen? Yes, he would. Within a few days, van Dokkum, a Yale University astrophysicist, and his former student, Gabriel Brammer, an astrophysicist at the University of Copenhagen spotted, in a mosaic image taken by the James Webb Space Telescope, one of the rarest of space oddities: a complete Einstein ring. A shining halo of light—a trick of gravity—that occurs when two galaxies line up perfectly, one behind the other, in our sky.

This is one of the wonderful things about Einstein rings. "There's actually nothing there, where you see the ring," van Dokkum says. If you were traveling in a spaceship toward it, the Einstein ring would seem to get larger at first, but then it would slowly disappear. "That's the mind-bending aspect," he says. So mind-bending that Einstein himself once referred to the idea of a complete observable ring as a "science-fiction effect." They only exist, as Obi-wan would say, from a certain point of view. And yet, by analyzing their size, researchers can decipher clues about some of the more vexing questions in the universe, such as when giant galaxies began forming and the mysterious nature of dark matter.

If Einstein rings are rare, complete ones—like this one, that van Dokkum and colleagues detailed in *Nature Astronomy* in October—are almost unheard of. Tony Stark, (not Iron Man but) an astronomer and cosmologist at the Harvard Smithsonian Center for Astrophysics, explains that it's "unusual for the chance alignment to be so good that a nice, round 'Einstein Ring' is produced." Einstein rings are "the most elegant manifestation," as NASA puts it, of a beguiling astrophysical phenomenon called gravitational lensing.

The massive galaxy closer to us—the dot in the ring—is acting like a giant lens. A lens, like a magnifying glass, can alter how an object appears by affecting the path light takes to our eyes or instruments. Magnifying glasses focus light rays together, which make an object appear larger, or closer, than it really is. Van Dokkum says what happens with gravitational lenses is that a

Dark matter is the stuff that holds galaxies together.

lot of light rays that would otherwise pass by the Earth (or, in the case of a magnifying glass, not fall on your retina), get bent toward us. "That magnifies the total amount of light that we get from these objects. Gravitational lenses do exactly what an optical lens does—they magnify," van Dokkum says. "You can get these images of distant galaxies with much higher resolution and intensity than we otherwise would be able to get, even with James Webb."

The galaxy acting like a lens at the center of the Einstein ring van Dokkum found is the most distant lens ever discovered, at least at the time they spotted it. Its light had been traveling for 10 billion years, appearing as a dot within the ring. The light from the ring itself had been traveling for 11.5 billion years.

Van Dokkum says the complete Einstein ring offers "further evidence that massive galaxies started forming very early in the history of the universe." This has been a niggling question on the minds of many cosmologists since early 2023 when Webb Telescope images showed unexpectedly large galaxies hanging around soon after the Big Bang. According to current cosmological models, van Dokkum says, the massive

GRAVITY'S HALO A massive galaxy can curve spacetime enough to bend light toward us that would otherwise pass us by, allowing us to see a far away galaxy from directly behind a closer one, but smeared out into what Einstein called a "luminous circle" surrounding the galaxy closer to us.

COURTESY OF *NATURE ASTRONOMY*

galaxies shouldn't have had time to form that early. "The big question of those is: What is their mass? How heavy are they?" he says. "This galaxy inside the ring is a descendant of those very early galaxies. But instead of finding that we overestimated the masses, it looks like we may have underestimated the masses—so, exacerbating the problems, if you will, in understanding how so much mass could form so early" in the history of the universe.

Claudia de Rham, a theoretical physicist at Imperial College London and author of the forthcoming memoir *The Beauty of Falling: A Life in Pursuit of Gravity*, says this complete Einstein ring offers a new cosmic tool. "It allows us to infer the mass of the objects between the source and us, and get a much more precise mapping of the matter distribution in the universe," she explained in an email. And some of that matter seems to be behaving differently than expected. "In this case, it is remarkable that the observed level of lensing seems to suggest a higher than standard dark matter density at that scale."

Dark matter is the stuff that holds galaxies together. Without it, they'd fling apart, disintegrate, by the force of their rotation. Something, some amount of mass, has to be keeping them whole, something other than the mass scientists can observe, because the amount of matter they can see doesn't exert enough gravity to counterbalance galaxies' spin. This something-else is "dark," and hard to study, because it doesn't seem to interact with light in any way. Scientists don't yet know how to directly detect the stuff, but they can estimate how much dark matter a galaxy *should* have, given the amount of mass that's visible in stars. Which is where Einstein rings come in.

They offer scientists another way to estimate the mass of a galaxy—by measuring how dramatically it is lensing a galaxy behind it. Rare, complete rings give researchers the opportunity to make a clean measurement of the ring's diameter, and thus how massive the lensing galaxy must be to produce that effect. The bigger the ring, the more mass—some of it coming in the form of dark matter—the lensing foreground galaxy must have. And that can usefully differ from the mass estimate scientists might make from a galaxy's visible stars plus the amount of dark matter the galaxy *should* have. Researchers have even used Einstein rings to assess what sort of material dark matter might be, based on how different material might look after getting distorted by a gravitational lens.

If Einstein rings are rare, complete ones are almost unheard of.

From a stargazer's perspective, the ring van Dokkum and his team found is absolutely minuscule. You wouldn't even be able to see the ring with the most powerful ground-based telescope, because Earth's atmosphere would distort the image. "It would just be a blob," van Dokkum says. Yet the ring was bigger than he expected.

"Even if you account for dark matter, we can't quite explain the large diameter of this ring," van Dokkum says. He surmises that, judging by the ring's size, the galaxy in the middle of it—the bright dot in the image—has to have something like 10 times the mass of our own galaxy, the Milky Way. "It's partly dark matter, partly stars that we see. But there must be something else." The size of the Einstein ring suggests the lensing galaxy has more mass than the amount of visible stars in the galaxy could add up to.

"They're different by a factor of about six. That's weird," says Chiara Mingarelli, an astrophysicist at Yale University. She liked the way van Dokkum tried to suss out how much of the missing mass in the galaxy might be dark matter, or something else. "If I say that it's all dark matter—can I actually explain it that way?" she says. Not entirely. It's a better match—between the mass that the ring size indicates, and the mass that the visible stars indicate plus some dark matter. "But it's still not clear that it's actually all dark matter. The tension is there. They can't solve it."

One possibility is that there are tons of stars hiding near the center of the massive galaxy that our instruments can't quite detect. "Maybe there's stars there that are half a solar mass that aren't very luminous," Mingarelli says. "If you could see them, then you would get the right number." Another possibility is that van Dokkum and his colleagues aren't accounting for all the dark matter. "We use computer simulations to estimate how much dark matter there should be," he says. "Maybe we're missing dark matter. But that's a puzzle that requires further data."

The Einstein ring also got van Dokkum to reflect on the way he and his colleagues often work. "Now that astronomy has turned into this big science, we get giant datasets, and we run automated algorithms to find millions of objects. Which is all great and very important. But you cannot be surprised easily that way," he says. "You cannot find things you don't expect easily," because you're not looking at real images with your naked eyes. For that reason, Van Dokkum says the way he and Brammer stumbled upon the ring was, "in a way, very old fashioned." They were mining for gold in a viewer for Webb images Brammer had made that you can pan around in, and zoom in and out, "like Google Maps," while cheerfully chatting over the messaging app Slack about what they were seeing.

"Just looking at data, for me, it's a joy," he says. "I hope that, for my students, these kinds of discoveries inspire them, when they get an image from the universe, to also take a look. There's a lot out there. The universe is filled with wonders."

BRIAN GALLAGHER is an associate editor at *Nautilus*. Follow him on X (formerly known as Twitter) @bsgallagher.

The Dark Side of Awe

Probing our sense of mystery and wonder

BY KEVIN BERGER

I **READ A BOOK LAST YEAR** that gave me the strangest feeling. I felt good about humanity. Human beings weren't a natural disaster. We weren't destined to kill everything on the planet, including ourselves. The awe we experience at music concerts, or under a carpet of stars in the mountains, could recalibrate the moral compass of the world. Awe leads "to goodwill, cooperation, and a transformed sense of self as part of a community," wrote the author Dacher Keltner, a professor of psychology at the University of California, Berkeley.

The book is called *Awe: The New Science of Everyday Wonder and How It Can Transform Your Life*. Although my image of hell is a library of self-help books, I was won over by *Awe*. The science and research are sound, the writing is fluid and engaging, and the examples of people whose lives have been transformed by awe are convincing. Stacy Bare, a traumatized Iraq war veteran, overcomes the suicidal voices in his head by taking up rock climbing, skiing, and rafting. His experiences of "wild awe" inspire him to dedicate his life to help other veterans shed their troubled minds in the outdoors.

Feelings of awe were at work in the Rwanda genocide.

As the days wore on after I read *Awe*, and bad news continued to unreel around the world, the glow of the book began to fade. Keltner's definition of awe—"the emotion we experience when we encounter vast mysteries that we don't understand"—felt sentimental to me. The emotion of awe, bonding people into communities, was the root of polarization—my tribe is better than your tribe, my awe tells me so. The book had some holes in it.

When *Awe* came out in paperback this January, I emailed Keltner and asked if he was game for hearing out my misgivings. He was. In a video chat from his home in Berkeley, Keltner was affable as can be, his every word the expression of the diligent scientist. We talked a little about his personal life. He came of age in Hippie, California, which is not a place, of course, but a way of being. His father was a painter and his mother taught poetry and literature. In the 1960s, Keltner and family lived in Laurel Canyon, land of "Our house is a very, very, very fine house, with two cats in the yard."

You write, "History so often follows the ebbs and flows of awe." I know you mean that in a positive way, but I have to say, I see it as the problem. The sense of awe and its concomitant loss of self is exactly what leads people to fall under the spell of awful people, leading to awful outcomes. What do you think?

I think you're right. Feelings of awe were at work in horrible things like the Manson murders or the Rwanda genocide, where people were chopping off heads with machetes. Our research has found that awe reduces polarization. Our default experience is to sense a common humanity with others, to empathize. I thought the experience of awe would decrease the boundaries between in-groups and out-groups, not do the opposite.

PAGES 74-75: CREATIVE TRAVEL PROJECTS / SHUTTERSTOCK

NATALIE KELTNER-MCNEIL

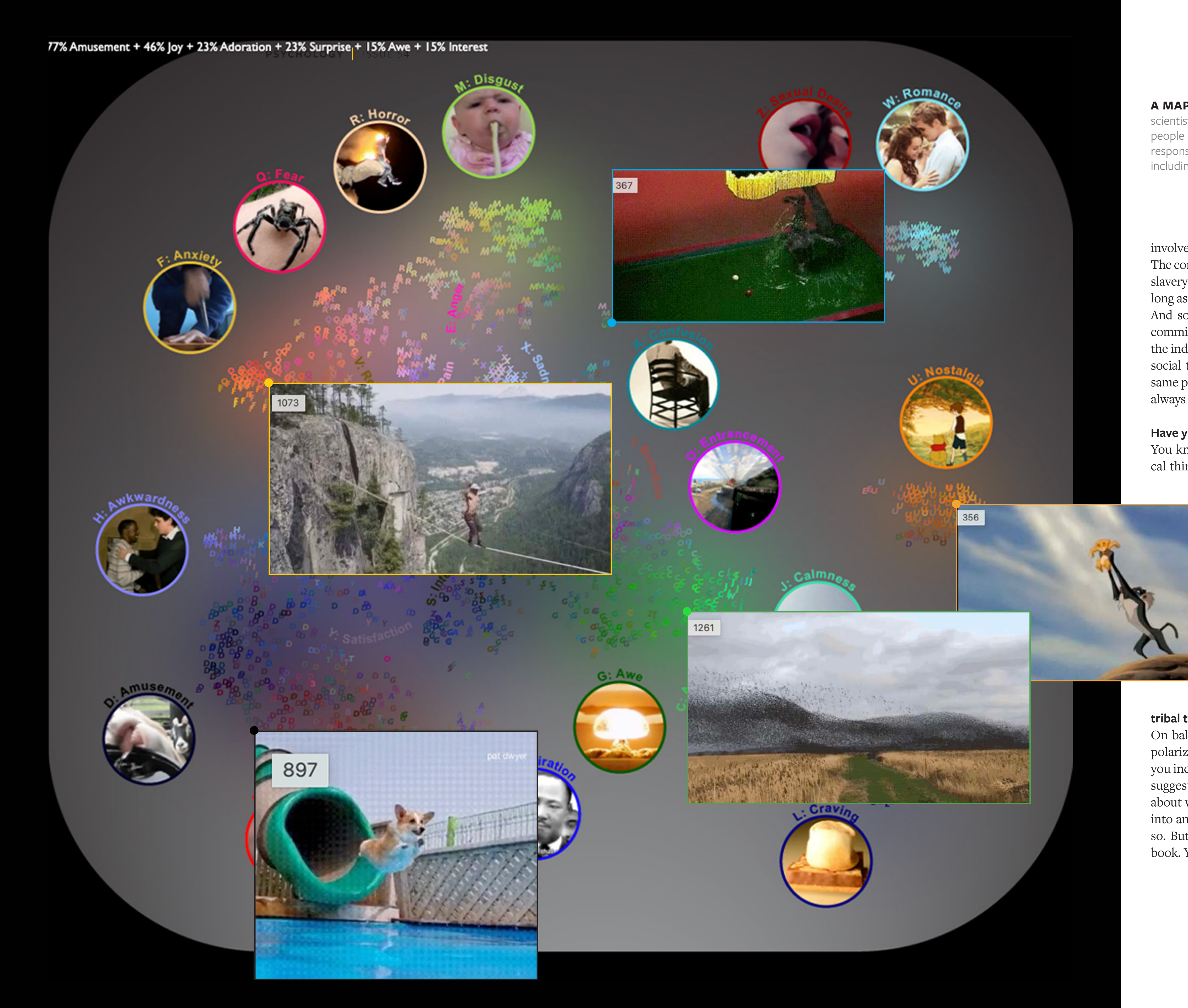
AWESTRUCK "I grew up in a weird, class-free world of hippies and the rural poor," says Dacher Keltner. "I went to Stanford and it was full of social class. I was like, 'Oh, my God, it's like Marx said, this is reality.' And I didn't even know about it!"

When have you experienced the dark side of awe?

When I read that Philip Gourevitch book about Rwanda, it gave me a shudder and even goosebumps about the horrors that people can perpetuate.[1] Today, we talk about moral panics and moral contagions, where a collective of people is captivated by a big idea, and they lose their sense of self, harm, and morality. And when I read the book, I was like, "Man, there's a lot of chanting going on, and dancing, and collective movement with machetes." It was driven by this whole systemic idea of how the Tutsis were undermining Rwandan society. I thought, this is just like what I do. I go to a dance group where we have a shared experience, we dance, we move together, we feel like we can conquer a big problem like the climate crisis.

Awe "quiets the nagging, self-critical, overbearing, status-conscious voice of our self or ego," you write. But that abandonment of self is what makes people vulnerable to demagogues. For some reason, I'm thinking of that overwrought movie version of Pink Floyd's *The Wall*, which makes a connection between a rock concert and a Hitler rally. But in terms of awe, maybe that link makes sense. The emotion at the concert and rally is the same. Might that undermine your thesis about the social benefits of awe?

No, it doesn't. A lot of religious and spiritual practices, forms of awe, reduce the likelihood of depression, they benefit life expectancy, and they make people happier. But I know what you're saying. Those experiences may be



A MAP OF EMOTIONS Dacher Keltner and emotion scientist and AI researcher Alan Cowen showed more than 800 people 2,185 emotionally charged short videos to elicit their responses. They discovered 27 distinct emotional experiences, including awe.

involved in religions that are racist, oppressive, and sexist. The compassion we feel in religious experience has justified slavery. "I love my people, I love all children of God. Just as long as they're not people of color, not indigenous people." And so, you have a case where awe leads to a collective commitment that's bad for sectors of society but benefits the individual. There's always that tension in society. Every social tendency that can lift up the greater good has the same power to wipe out huge sectors of society. And so, we always have to be critical. We need your critique.

Have you researched the power of charisma?
You know, I haven't. There's a new movement in political thinking that says political social movements happen because of singularly charismatic people who make you feel goosebumps. We haven't gotten to that in my field of psychology. But I think most people would say, yes, that happens. When Nelson Mandela came out of prison, I was at an event with 50,000 people weeping and we're like, "I'll do anything!" So, yeah, this power is real.

And dangerous.
Yeah, I hear you. We're a susceptible species.

You write, "The awe felt in encountering humanity's better angels can counter toxic tribal tendencies." How so?
On balance, the evidence we've gathered is awe reduces polarization and increases charity. Moments of awe make you include different people in your sense of tribe. So that suggests awe counters "othering." But if you're talking about white supremacists beating up immigrants, you get into another level of analysis. Can awe counter it? I think so. But it's one of the big questions that was left by the book. You're one of the first to get at this question hard.

But as fine-grained emotion scientists, let's get precise in what we're documenting. I get a lot of questions about Trump supporters. And when I look at Trump rallies, I don't see awe, I see rage. Yes, you feel rage collectively. It's awesome to be with 18,000 enraged supporters. But is awe really a proximal determinant of rage or genocidal tendencies? All emotions can be shared collectively. We can share humor and love and compassion, and we can share rage. So that's the critical test. I can use scientific measures to ask whether these emotions are shared experiences of awe. Or are they really about shared pride and rage? It's an empirical question that deserves research.

Experiences of awe seem fleeting. The other emotions in our daily lives seem to drive awe away. Would you agree?
Well, all emotions are fleeting. They lead to shifts in your neurophysiology for 30 minutes at most. And parts of the emotion or conscious elements of it are very fast. So, yeah, they are fleeting and ephemeral.

But awe is interesting because it really changes how you think about the world. You think, "I'm part of something larger than myself." We've documented benefits of awe that last for a week. You go river-rafting for half a day and your mind is blown. And a week later, you feel less stress.

But you're asking the hard questions, Kevin, and this is a big one: How much and for how long will awe shift you? The literature shows psychedelic experiences are transformative. But how do you feel a month later? I don't think we want a human psyche or nervous system that is so shifted by these momentary emotions. We prefer homeostasis, we like to return to baselines. Awe can get you into trouble. "Yeah, I'll just stop working and paying the bills, and I don't need to eat." But the literature around happiness and gratitude suggests the effects of awe may last longer than other momentary emotions.

Awe reduces polarization, as you say. How do you think that happens? Do experiences of awe get us to let down our ideological guards?
First, here's what I like about awe. It points toward what is meaningful to you—the significant moral themes that matter to you. Do you care about social justice? Beauty? Pleasure? Do you care about harm? Community? Awe makes you more aware of the big narrative or ideology, the political ideal, that you want to be a part of. And every individual is different. We all resonate with different moral political themes. And awe shines a light on that. A healthy society should allow for multiple ideologies.

What's more, we've learned that awe increases your perspective. It makes you less polarizing, more rigorous in your thoughts. So, let's hope the reliable experiences of awe don't make you vulnerable to the kind of simplistic forms of reasoning that are part of an ideology. Let's hope it makes you pluralistic, makes you recognize there are multiple views, including ideological views. So, that's the first part. We don't know the second part, whether awe can make you become less ideologically fixed in what you care about.

Isn't awe just an emotion for the privileged?

You define awe as occurring "when we encounter vast mysteries that we don't understand." But that sounds incomplete. What I think is more awesome is getting to know how the mystery works. The more I know about a piece of music, the more I enjoy it. Do you know what I mean?
I do, and you're hitting the deep theme of the book: Awe is fundamentally about mystery. It cues the human mind to construct meaning, make processes, to understand mystery. Why do I die? Let me construct a theory about that. Why are there so many biological forms in the world? Let me arrive at a theory of evolution. Both Newton and Descartes asked, "Why are there rainbows?" So, they construct color theory and math and physics to figure it out. It's just who we are. Mystery is the engine of creativity.

Is awe universal? I ask because, as you know, there's a relatively new science of emotions that says emotions aren't hardwired reactions. Rather, emotions are concepts constructed by our brains, and so emotions like awe can vary from individual to individual, culture to culture.
We published a paper in *Nature* that the expression of awe is about 75 percent universal.[2] When people from around the world see fireworks or shooting stars, their "Whoa!" speaks to a universality in their facial and vocal responses, and in getting goosebumps. So, there's a deep mammalian, universal structure to awe.

But don't individual cultures shape our perspectives and emotions?
They do. But—you've touched a nerve—you have to consider individual differences within a culture. If you look at individual differences statistically, they beat cultural influences time and time again. Our natural selections form variations. We are more similar across cultures than we are across individuals. You can find Chinese individuals like me temperamentally; we're going to have similar emotional lives. That's predicted by evolutionary thinking. And you can't account for that from constructivist views.

What's really interesting is how culture constructs things out of emotions.[3] Culture elaborates on emotions, adds details, adds objects of consciousness. You go to China and hear traditional music and it's different

PAGE 78: COWEN & KELTNER, *PNAS* (2017)

It's just who we are. Mystery is the engine of creativity.

from music in other cultures. We dance in one way in the west and other people dance in another way. I feel awe about the story of the Buddha. And somebody in a Pentecostal church is thinking about Jesus. So, yes, there's differences in cultures, but in all the stories we've gathered, from 26 countries of every persuasion, there's universality. And by the way, I don't know why people fear universality.

Maybe because it undermines our individuality and unique cultures.
I don't know. I think it echoes social Darwinism—my group's better than yours. But in fact, universality is the antithesis of social Darwinism.

Why do you think the emotion of awe evolved?
I put it down to the realm of self-transcendent states, which get us beyond self-interest. It's fundamental to human survival to be part of a community, to do things collectively, to alloparent, to share food. You need a whole suite of processes to orientate to other people's interests and welfare. Awe does that, it makes you more collaborative and cooperative; you feel like you're part of a social network. It also has effects on cognition that get you to shift out of an analytical mode and to see the systems around you. It's like, "Oh, I get it, I'm not just me, I'm part of this community." Awe is vital.

You write that "awe promotes the reverential treatment of nature." Sometimes when I'm on a hiking trail, I'm not so sure.
I think there are many risks and perils associated with the pursuit of awe. We travel to remote parts of nature, swim near reefs, and all in the search of awe, blind to what this pursuit is doing to the cultures and ecosystems, not to mention the carbon emissions of flying there. I think a prime example of this is the "psychedelic tourism" right now, where Western Europeans are in search of personal enlightenment traveling to Mexico or the Amazon, often at great expense to the cultures they visit, and their ecosystems. Any emotion can lead us to trouble, and this is one of awe's great perils, that in its commodification or self-serving expression, the pursuit of it can undermine its very point, which is to lead us to benefit those around us and the ecosystems we are part of.

You tell us it's a myth that awe is reserved for those who can afford to indulge in it. In fact, you write, "Wealth undermines everyday awe and our capacity to see the moral beauty in others, the wonder of nature, or the sublime in music and art." How does wealth undermine awe?
Oh, man. When I first started studying awe, everybody was like, "Isn't this just an emotion for the privileged?" But the opposite is true. Wealth comes with a sense of transactionalism, which is counter to the expansiveness of awe. Wealth tends to amplify your sense of self-interest: The wealthier I get, the more individualistic I become, the more I am aware of my own desires and interests. That's a countervailing force to awe. Because wealth makes you more solitary, more inclined to spend time on your own, you're less likely to share feelings of awe. Here's yet another reason why our culture is struggling, why economic inequality is such a problem.

What's the best example you can cite to show awe is not reserved for the well-off?
The blues. I would argue the most important music in the United States is African-American music. And that music comes straight out of slavery. The blues and gospel music are a form of awe and awe-based expression and creativity. And we should take spirituality, too. Spirituality tends to track to lower socioeconomic conditions. The spiritual imagination tends to be activated by states of deprivation.

How so?
Trauma and illness and death destabilize our sense of safety, our sense of integrity, our sense that the world is predictable. Destabilizing our sense of who we are is horrifying. When I interviewed Stacy Bare about his years in combat in Iraq and Afghanistan, he said he was always oscillating in a mixture of horror and fear and terror and awe. But when we encounter trauma, or are in a state of physical deprivation, the mind gets to work. It says, "Let me, through the power of mystery and awe, arrive at a new understanding of the world. Let me make sense of this."

KEVIN BERGER is the editor of *Nautilus*.

FOOTNOTES

1. Gourevitch, P. *We Wish to Inform You That Tomorrow We Will Be Killed with Our Families* Farrar, Straus and Giroux, New York, N.Y. (1998). Page 29: "There were many attackers, Samuel recalled, and they came from all sides—'from the church, from behind, from the north and south. We heard shots and cries, and they chanted the slogan, Eliminate the Tutsis.' "

2. Cowen, A.S., *et al*. Sixteen facial expressions occur in similar contexts worldwide. *Nature* **589**, 251-257 (2021).

3. Keltner, D. & Oatley, K. Social functions of emotions in life and imaginative culture. *Evolutionary Studies in Imaginative Culture* **6**, 1-20 (2022).

Why We Sense Somebody Who Isn't There

When expectations aren't met, our brains spook us

BY PHIL JAEKL

FOR 10 MONTHS, ERNEST SHACKLETON and his crew, bound for the South Pole, were stranded in Antarctic ice. The massive pressure of the ice was slowly crushing their ship, HMS Endurance. When the ship began to break apart, the men abandoned it and camped on the ice. A few weeks later, the Endurance sank. The freezing days dragged on, but the men saw hope when their icy campground began to splinter, revealing a watery lane for their small boats.

In May 1916, the explorers set off for land, battling violent winds, currents, and ice floes. They rowed until their bodies were ragged. Soon they began seeing things: "resemblances to human faces and living forms in the fantastic contour and massively uncouth shapes of berg and floe," Shackleton wrote in his account of their survival, *South*. During a 36-hour trek over mountains and glaciers, with two crew members, Shackleton wrote, "it seemed to me often that we were four, not three." Inspired by Shackleton's account, T.S. Eliot wrote in "The Wasteland," "Who is the third who walks always beside you?"

She reported an invisible man clasped her in his arms.

HE SAW THINGS Ernest Shackleton, photographed during his HMS Endurance expedition, exemplifies how dire conditions can set the brain reeling. On a trek across ice seeking rescue, he wrote, he and his crew began seeing faces in the "massively uncouth shapes of berg and floe."

FMSKY / WIKIMEDIA COMMONS

Who indeed? Now, cognitive scientists have taken up the quest to explain the mysterious third. The felt presence of an unseen person, they have found, results from breaks in the neural connections that normally link expectations and actual experiences. During extreme conditions, or when the connection is broken and actions don't meet unconscious expectations—a sign of land, a rescue team—our brains feed our minds a phantom substitute.

Ben Alderson-Day, an associate professor of psychology at Durham University, in the United Kingdom, and author of *Presence*, winner of a British Psychological Society's Book Award for 2023, says it doesn't always take Shackleton-like extremes to generate a felt presence. "People often describe a very distinct feeling that someone is there with them when they're drawn into some sort of social situation where they need to act or change their position to make themselves safe," Alderson-Day says.

Psychologists and neuroscientists have long believed this felt presence may link the sense of ghosts, spirits, phantoms, wraiths, specters, and apparitions, across all cultures. An early theory pioneered in the 1980s by psychologist Justin Barrett, attributed supernatural agency to a "hyperactive agency detection device," a neural mechanism that biases us to presume the presence of purposeful agents. Its existence stems from our evolutionary success of erring on the side of caution when it comes to detecting predators. Around the same time, the late psychologist Michael Persinger began his notorious "God Helmet" experiments. He created weak electromagnetic fields in a motorcycle helmet, which participants wore while undergoing sensory deprivation. Persinger claimed he could induce a presence, often in the form of God, in 80 percent of participants. (Nearly all replication attempts failed to confirm the effect.)

Most recently, neuroscientist Olaf Blanke, a Swiss-German neurologist working in Lausanne, is using more rigorous methods than Persinger. While evaluating a 22-year-old woman for epileptic surgery, his team serendipitously discovered that it's possible to induce neural activity that consistently elicits a felt presence. The procedure involved stimulating specific parts of her brain with electrodes, a fairly common technique that can produce a variety of hallucinatory sensations and perceptions. But this time, after a small electrical zap, she reported the clear yet unseen presence of someone behind her. During subsequent stimulations, she reported a man clasped her in his arms.

The stimulated region, called the temporoparietal junction, is where the temporal and parietal lobes of the brain meet. It is heavily involved in processing corporeal information relative to oneself and to other bodies. Damage or malfunctioning here can induce strange, out-of-body experiences where one views a remote, disembodied perspective of their own self. Aberrant functioning can also distort what are normally clear distinctions between oneself and others, where you end and something, or someone, begins.

To explore bodily illusions, Blanke and his team created an experimental device that seemed inspired by a Philip K. Dick novel. Participants wear a haptic sensing device that tracks their finger motion while they make poking movements into empty space in front of them. These movements are then replicated by a robot

Under stress, our brains feed our minds a phantom substitute.

PAGES 84-85: TASNUVA ELAHI; WITH IMAGES BY ALLA_LINE AND ILLUSTRATION FOREST / SHUTTERSTOCK

behind them, which they can't see, that pokes them in the back. When a delay between the participants' movements and the felt pokes is introduced—disrupting the causal relation between action and sensation—the participants attribute the pokes to an unseen but felt agent. Fosco Bernasconi, a senior scientist working with Blanke, explains that an impairment to self-body signals "causes the brain to misinterpret its own body signals and attribute them to somebody else."

A neurological model of motor control, formally known as the forward model, says that whenever we execute movements to carry out an action, we create predictions in the form of neural body signals—called "efferent copies"—that allow us to anticipate the sensory consequences of our actions. When this causal relation gets disrupted by say, a delay, and the sensations deviate from our expectation, our brain can resolve the mismatch by attributing them to the actions of someone else. It makes sense, Alderson-Day says, "that if you disrupt sensorimotor signaling, you have an illusory body turn up."

Blanke's model provides a plausible mechanistic account to explain the feeling of a presence, but one explicitly tied to the activation of the motor system. In contrast to the experience of meeting God while seated and motionless, as Persinger claimed his experiments showed, Alderson-Day explains that Blanke's work "is more focused on the clinical and neurological correlates of very distinct presence experiences—separate from the spiritual and ecstatic."

What originally inspired Alderson-Day to investigate felt presence was a patient who constantly heard a voice. The patient didn't have to perform any action to hear the voice, he just expected to hear it at any given moment, as if it was always "there." Such motionless presence experiences fit well with another theoretical candidate for explaining their neural basis, called predictive processing, which holds that when one has high unconscious predictions or expectations of events, they can generate a bias that overrides perception.

Predictive processing is a revolutionary theory because it overturns the notion of perceptual experience as constructed primarily from incoming sensory signals. It implies, rather, that experience arises from a continually updated mental model of the world. Our brain is constantly generating predictions of sensory inputs around us. If we encounter something new, our brain may initially provide a faulty prediction, but in time, with more information, it tweaks the model to fit the reality.

The theory goes a long way to explain the massive amount of brain connections involved in making sense of the world. (Incoming sensory signals alone only comprise 1 to 2 percent of the brain's energy consumption.) And how easily our perceptual experiences can go astray. Alderson-Day says that even mild disruptions between expectation and experience can result in the perception of a presence. "Predictive processing basically says that we all have the propensity to experience presences and other hallucinations, because we all rely on expectation to some degree in our perception of the world."

In freezing Antarctica, it wasn't only the extreme circumstances that gave rise to the "third who always walks beside you," it was a precise set of unconscious processes born out of the misery that Shackleton and his men found themselves in, and the dire need to find their rescuers. These processes are universal in all of us, and so the next time you sense somebody who isn't there, you might reflect on why that should be.

PHIL JAEKL is a freelance science writer and author with an academic background in cognitive neuroscience. His latest book is *Out Cold: A Chilling Descent into the Macabre, Controversial, Lifesaving History of Hypothermia*. He lives in the Norwegian Arctic in Tromsø.

WABENO / SHUTTERSTOCK

The Bittersweet Science

Boxing is reputed to fight Parkinson's disease. I put on the gloves to find out.

BY MARK MACNAMARA

THE NOTION OF BOXING as the "sweet science" is often thought to have been coined in 1956 by the great *New Yorker* writer A.J. Liebling. He used the term as the title of his definitive book on the sport, but he took it—with much appreciation—from a British sportswriter, Pierce Egan. In 1813, Egan wrote about the "sweet science of bruising" in his master work, *Boxiana*. The book is a collection of magazine pieces set in a bloody, bare-knuckled world opposite Jane Austen's.

As for the "sweet science," no one ever really defines it. A carefully thrown knockout punch to a sweet spot on the chin is one possible derivation. There's also the play on a science with so little apparent sweetness. But that's not it. The sweet science Liebling and Egan describe had more to do with British principles of "stoic virtues," "generosity," and "true courage"—altogether, life in a contradictory place. It's a square ring, after all, where sometimes hope transcends the specter of an awful inevitability.

Or so I've come to think, on a journey I've begun in the past year, exploring how the sweet science can be used as a treatment for Parkinson's disease—that increasingly common degenerative disorder of the nervous system, tied to a loss of the brain chemical dopamine, which is involved in movement, memory, motivation, and cognition.

In October 2022, a longtime tennis partner noticed something "strange" in my stride, along with a noisy shuffle. "Fatigue," I replied with pique. The truth is I'm 75 and had known something might not be right for years, particularly the ominous hand tremors, as well as the night-of-the-living-dead gait and a facial expression to match. Add severe anxiety in public places and bizarre nightmares, some quite disturbing.

I found a specialist to resolve the matter. We talked on the phone. "I don't think you have Parkinson's, but why don't you come in," she said. I did and within minutes she changed her mind. She was struck by the tremors on both my left and right side, and by some other more subtle indications, like an occasional difficulty in swallowing. She recommended a physical therapist to conduct the Mini-BESTest: Balance Evaluation Systems Test. Among the challenges: you stand on one leg for 20

> Someone told her she moved like a wavy wind sock outside a used car lot. "Exactly how I feel," she said.

seconds then the other leg; walk quickly up and down a hallway, while looking up and down, then to the left and right; stand in a corner on a cushion with eyes closed, not touching the wall. Finally, the therapist holds on to your shoulders and tries to pull you down from behind.

I enjoy these kinds of tests and did well enough that the physical therapist thought I was on the bubble, at least in terms of balance. She suggested I return in six months and brought up the matter of meds. I explained that I ran regularly and would like to depend on natural dopamine for as long as I could. Exercise has long been known to boost dopamine. One of the cruelties of Parkinson's is that there is no blood or other test to confirm it. But if certain meds like Carbidopa-Levodopa cause certain symptoms to subside, then you probably suffer from it. Probably. Or, perhaps you have a variation, which may be even more debilitating.

In the end, I surrendered to the meds, but in the six months before my diagnosis became clearer, I kept with the delusion that I was athletic enough to generate my own dopamine, and so I began running several miles a week. Then one day a friend asked if I'd heard about Rock Steady Boxing. I hadn't. "Well," they said. "You should try it. Might sound counterintuitive, but you don't really hit anybody. It's about redoing the wiring."

ROCK STEADY BOXING was founded in 2006 by a 40-year-old prosecutor named Scott Newman and a two-time Golden Gloves boxer named Vincent Perez. At the time, Newman had been diagnosed with early onset Parkinson's. Perez drew Newman into a world focused on optimizing reflexes, balance, dexterity, and coordination. The two men worked six days a week getting Newman back in shape, using prolonged exercises done as strenuously as possible.

As Newman's health and spirits lifted, he imagined a business opportunity. It was to create a noncontact boxing program to help people in their struggle with both motor and non-motor symptoms. The scientific basis was to use intense exercise to stimulate the natural flow of dopamine. At the cellular level, dopamine also helps protect the nerve cells attacked by the disease.

Now, 17 years later, Rock Steady Boxing operates as a nonprofit organization headquartered in Indianapolis. Today there are nearly 900 affiliates across the country, and more than a dozen abroad.

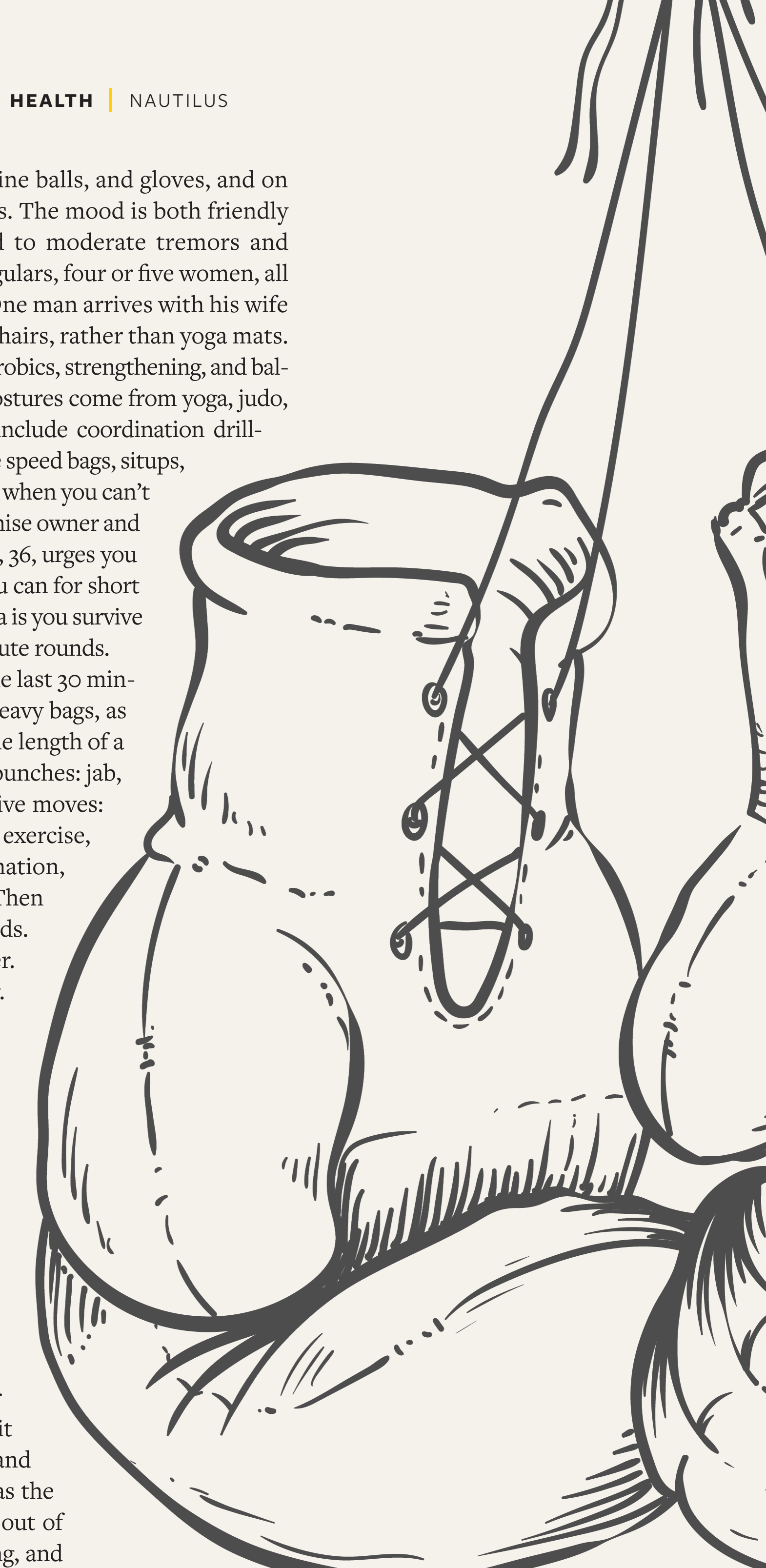
In October 2022, I began going to a Rock Steady Boxing gym at the southern end of Silicon Valley, in Santa Clara, near Levi's Stadium. It's a modest, two-ring gym called Relentless Boxing, equipped with a

farrago of bags, weights, ropes, tires, medicine balls, and gloves, and on the walls, poster tributes to local champions. The mood is both friendly and guarded. Most participants have mild to moderate tremors and mobility issues. There are at least a dozen regulars, four or five women, all mostly retirees over 50, a handful over 70. One man arrives with his wife to help him along. A few people work from chairs, rather than yoga mats.

Class includes three major components: aerobics, strengthening, and balance training. Also, core muscle stretching. Postures come from yoga, judo, jujitsu, and other martial arts. Calisthenics include coordination drill-stations such as jumping jacks, jump ropes, the speed bags, situps, and pushups—always as many as you can, and when you can't go on, the coaches, particularly the local franchise owner and head coach at Relentless Boxing, Rob Putnam, 36, urges you to keep going anyway. You work as hard as you can for short periods of time. Exhaustion is healing. The idea is you survive Parkinson's by thinking in terms of three-minute rounds.

The daily routine varies but often it's in the last 30 minutes that you put on the gloves and hit the heavy bags, as hard and fast as you can for three minutes, the length of a round in the ring. Boxing features four core punches: jab, cross, hook, and uppercut. Add basic defensive moves: bob and weave, advance and retreat. In one exercise, you quickly memorize a six-punch combination, which might include punches and moves. Then you box for 60 seconds. Rest for 10 seconds. Then another combination, rest, and another. You're working mind and body, ever faster. As you become proficient, over months and years, Coach Rob urges you to visualize the heavy bag as an actual opponent, so you imagine facial features, body type, strengths, and weaknesses. The purpose is to sharpen focus, personalize, tune the signals, and learn to be meticulous.

The most satisfying part of a class is when the coach puts on his mitts, not unlike a catcher's glove, and invites you to punch him. Or her. The coach literally catches your punch. This is the closest you get to real contact. The coach calls out punches by name or number (1 for jab, 2 for cross, etc.) and you hit the corresponding mitt. If you're skillful, and resilient, you get into a rhythm. You hear it as the gloves make contact. You're working in and out of range of your opponent, bobbing and weaving, and it all becomes an aesthetic, a kind of dancing.



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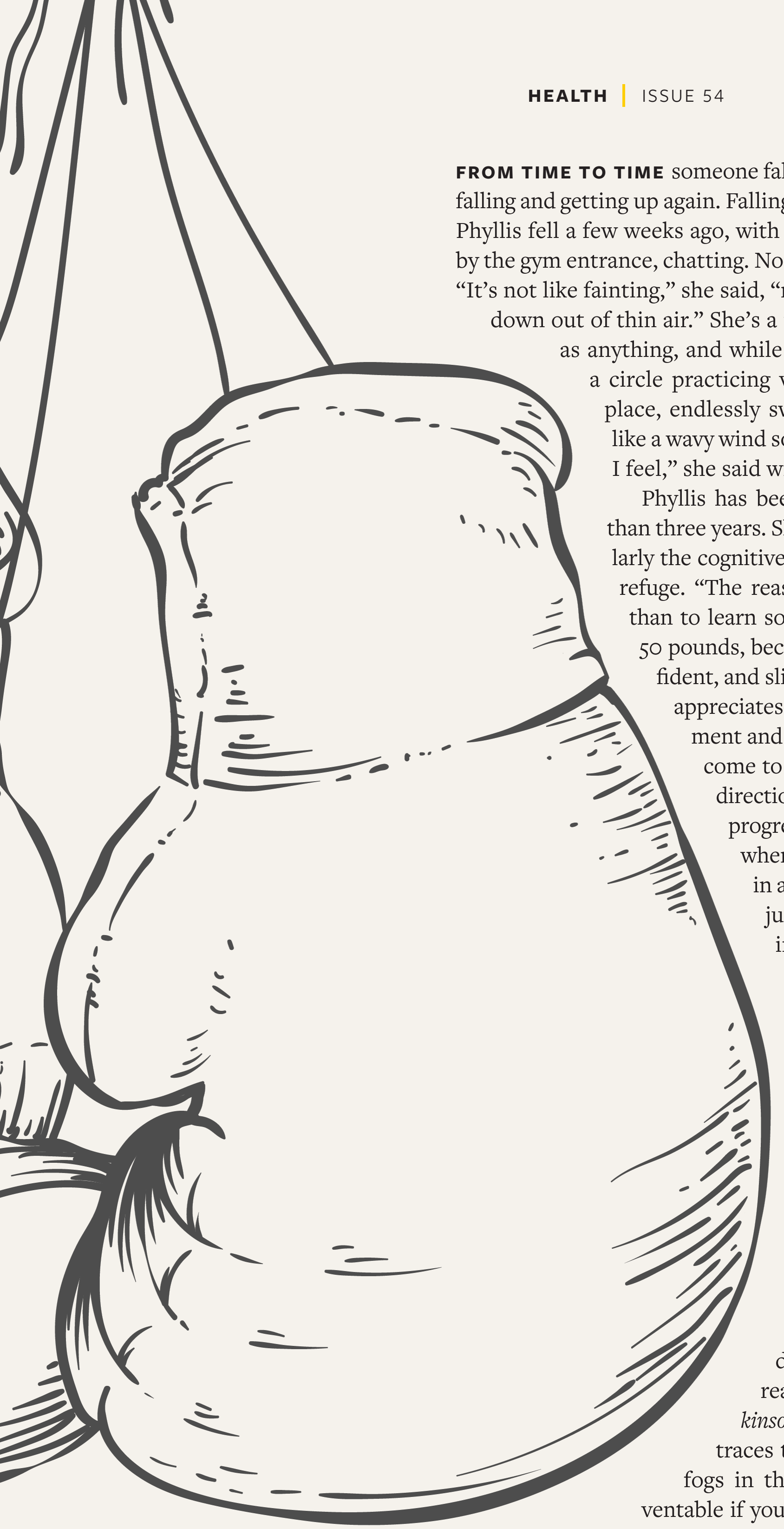


FROM TIME TO TIME someone falls in class, which includes exercises for falling and getting up again. Falling is the great menace with Parkinson's. Phyllis fell a few weeks ago, with hardly any warning. She was standing by the gym entrance, chatting. No need for an ambulance but unnerving. "It's not like fainting," she said, "more as though gravity had pulled you down out of thin air." She's a retired teacher, ever optimistic, sweet as anything, and while at the beginning of class we stand in a circle practicing voice exercises, she moves around in place, endlessly swaying. Someone told her she moved like a wavy wind sock outside a used car lot. "Exactly how I feel," she said with a smile.

Phyllis has been with Rock Steady Boxing for more than three years. She finds it enormously helpful, particularly the cognitive aspect. Rock Steady Boxing is her one refuge. "The reason I joined was less for the exercise than to learn something new," she told me. She's lost 50 pounds, become calmer, less frustrated, more confident, and slightly more coordinated. She especially appreciates the way coaches can read her movement and suggest ways to retrain her body. She's come to depend on the immediate effect these directions often seem to have. And yet as much progress as she's made, she still has moments when her legs freeze. She told me she was in a nightmare running through a field and jumping a hurdle. "Actually, I was throwing myself out of bed. It's happened before. I've had several black eyes. The worst was when I hit my face on the nightstand and broke my nose."

Before and after class, people exchange tips. "This neurologist returns calls, not that one." "So-and-so is going to have Deep Brain Stimulation." "Have you heard about the work of Peter Tass at Stanford who has developed a vibrating hand glove that may have a profound effect on Parkinson's?" "If you have Parkinson's, how do you explain to your children they may inherit it?" "You've got to read Ray Dorsey's new book, *Ending Parkinson's Disease, a Prescription for Action*. He traces the disease back to the London smoke fogs in the 1870s. He says Parkinson's is preventable if you can limit your exposure to the deadly

COURTESY OF ROB PUTNAM

COACH ROB After beating childhood cancer, Rob Putnam went on to become a featherweight boxer. Now he's the head coach of the Rock Steady Boxing program in Santa Clara, California, helping people fight Parkinson's disease.

chemicals around us, like the children who worked as chimney sweeps in the 1700s defeated scrotal cancer."

In these conversations at the gym, there are always the questions underneath: Does Rock Steady Boxing really work? And for how long and under what conditions? The consensus among people I spoke with—neurologists, physical therapists, trainers, and participants—is that it does work. For me, it has. After a year, I've acquired strength and agility, although the arm tremors and awkward gait are about the same. Friends say I seem more energized and focused. The Rock Steady Boxing 1 to 5 scale, where 1 is high, meaning 1 is your goal, had me at 1.5 when I started and after 8 months, I moved up to 1. A subtle improvement but encouraging, if only for a moment.

Terry Ellis is an associate professor at Boston University who investigates the effects of exercise on the progression of Parkinson's. She's coauthor of a 2019 *Frontiers in Neurology* article on the effects of Rock Steady Boxing on Parkinson's, which offered a rather depressing conclusion: "Despite growth in the popularity of boxing for Parkinson's and some positive findings, there is limited evidence of efficacy."

Recently, Ellis took a much more positive position. Rock Steady Boxing, she told me, was "a great idea, a great program," but it's not about boxing per se. It's about how jabs, crosses, hooks, and undercuts get your heart rate up, just as aerobic, strength, and balance training do. She added, "There's been many rigorous studies that show aerobic exercise impacts the brain of people with Parkinson's and reduces the severity of motor symptom problems. Those studies also show aerobic exercise stabilizes the progression of Parkinson's." Still, the question remains how to keep adjusting the program over many years, especially for people who may face other illnesses.

KIMBALL MAGONI, 69, WAS DIAGNOSED with Parkinson's 10 years ago. He lives in Massachusetts and has been going to the same Rock Steady Boxing class for nearly five years. He's also a licensed clinical psychologist and these days accepts only Parkinson's

If you can rebuild self-acceptance, then you don't care what somebody in the restaurant thinks of your tremors.

patients. Magoni has become increasingly interested in the power of camaraderie to deal with the whole Parkinson's kit of grief, anger, loneliness, helplessness, self-pity, and shame. Many people, following their diagnosis, Magoni said, feel lost from their community.

"It's like coming home when you were a kid," Magoni told me. "If you had a happy house, a sanctuary you're a part of, that takes care of a whole lot of crap. You walk in, you're valued. That's what's so unique about Rock Steady Boxing. With the right group, people will connect, they will support each other, they will feel much less anxious about their Parkinson's. Why? Because they've got a place where they're back to being valued for who they are, not what symptoms they have, or don't have. They find their way through places like Rock Steady Boxing back into the tribe. And if you can rebuild self-acceptance, which is so critical, then you don't care what somebody at the next table in the restaurant thinks of your tremors."

Magoni noted that one benefit of Rock Steady Boxing is the feeling of control derived from boxing itself. Even if you're unable to stand, and box while sitting in a chair, you feel relief by being physically aggressive, active rather than passive.

Not long ago, I paid my regular visit to the physical therapist. Once more she gave me the Balance Evaluation Systems Test. The score had barely changed. In fact, the result was slightly better than six months earlier. The therapist was delighted. Yet there was something amiss. One exercise involved walking briskly a few yards to a cone and back, while counting down from say 100 in threes. I mangled it. Twice. Which was strange because a few months earlier I had no problem. The therapist shrugged. "No matter, this happens sometimes under duress. What else is going on in your life?"

A few days after the promising test score, I have one of my periodic nightmares. I'm hiding in a small room in the district attorney's office. I once served as the public information officer in the San Francisco DA's Office. In the dream, my archenemy is standing just outside the door. I'm terrified he'll discover me. I decide to rush him, make a last stand, howling as I go. And then as I crash through the door I see the face, but it's not my archenemy, whoever that might be, it's someone I don't recognize at all. I wake up and find myself hitting my wife with the back of my hand. She yells at me to stop and then firmly, without a word, she holds down my arm until I go back to sleep.

The next morning, I wake up with my daily unease, that whole kaboodle of dream bits and now new guilt, plus the ominous specter of insignificant tasks, the idea that I am slowly disappearing, and the worry over empathy's end—for others and myself. Fortunately, every other day there's the curative promise of the gym and the song of the speed bag. Today is on but I'm caught between the desire for solitude and the solace of others. I pick others.

When I arrive, Michael, a retired building contractor, greets me with his mantra about this being the one exclusive club nobody wants to join. We smile. We shake our heads. I look to see who else is there. Phyllis is swaying rhythmically to gym pop. Steve, on the speed bag, throttles it like a pro. And then there's Cyndie, a lithe, red-headed spirit and a former executive assistant

to a county health officer. She's been coming to Rock Steady for six years, she just turned 60. She joined Rock Steady Boxing on the recommendation of her neurologist at Stanford. Friends told her she was nuts. Her parents, churchgoers from the Midwest, were both supportive and very curious. They came to visit. She showed them there was no danger because there was no contact and anyway, she was the last person in the world with any interest in punching or being punched. They came round and over the years many of her symptoms have not progressed. "Frankly, I don't know if it works," she told me. "I think it does. All I know for sure is that I came initially out of curiosity, and now I stay for the comradery."

As people gather 'round, Coach Rob takes quick stock of how people are doing: who's on a peak, who's in a valley. He doesn't see plateaus with Parkinson's, he sees arcs: the man who arrived in a wheelchair and two years later discarded his cane and stood up to punch the bags; the man who was making good progress but then stopped coming, reclaimed old bad habits and declined. One truth about Rock Steady Boxing is you have to stay with it, and of course nothing is certain.

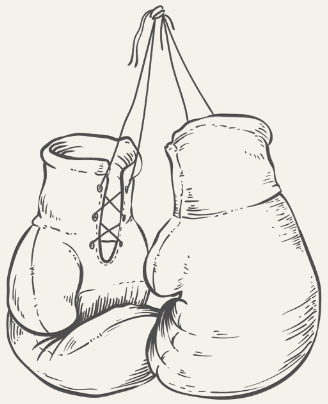
Rob was once a featherweight boxer by trade, 5'6", 147 pounds, reminiscent of Daniel Mendoza, a 5'7", 160-pound Jewish fighter from London's Whitehall district who in the 1780s became one of the great boxers of his day. He was distinguished by lightning glove speed, a mesmerizing ability to bob and weave, and, above all, to anticipate his opponent. He pioneered Muhammed Ali's rope-a-dope strategy and in 1789 started a boxing school devoted to technique. He also wrote a book, *The Art of Boxing*, in which he described the sweet science in terms of maximizing reflexes, balance, dexterity, and coordination—all aspects of the Rock Steady Boxing training.

Coach Rob had three bouts of cancer as a child, including a bone marrow transplant at age 9. At one point, all the other children in his ward had died. Doctors said his survival was due partly to the muscle mass he acquired learning karate at age 3 and partly to the martial-arts-style physical therapy he received in the hospital. He said he learned to "visualize my white cells literally beating up my cancer cells." Which led to his notion of imagining a face and arms on the big body bag. He told me he came away from childhood with an iron optimism based on the conviction that "I wasn't *allowed* to lose. That was my mother's doing. Each time the cancer came back she taught me to think of it as an opportunity: 'OK, well, I guess I get another fight.' Does that make any sense?"

Of course it does. And yet I'm not so rock solid in my own conviction. The metaphor that describes my orientation is not the ring but the high wire, where I feel as though I'm plodding along mile after mile, trusting that my good balance will save me, if I'm lucky, disciplined, and follow all the best advice. I've come to believe that Rock Steady Boxing works best that way—if you make it into a mission control center that brings together the newest exercise and medical strategies, and the power of the group.

I'm actually more loner than comrade. But I won't forget the fellow boxer who came up to me to ask if I could re-strap his glove, which had come undone. He looked exhausted and proud, stoic, and very thankful for my small help, thankful in a way that captured exactly the definition of the sweet science, which I now think of as an antidote to inevitability, an untightening of the fist.

MARK MACNAMARA, a writer and journalist based in Asheville, North Carolina, has written for such publications as *Nautilus*, *Salon*, *The Stanford Social Innovation Review*, and *Vanity Fair*.



What Physicists Have Been Missing

An exciting new theory reconciles gravity and quantum physics. I think it's wrong. But I may be too.

BY SABINE HOSSENFELDER

A CENTURY AGO, PHYSICS BREAKTHROUGHS came in rapid sequence. There was quantum mechanics and Einstein's theories of space and time, lots of new particles, two new nuclear forces, and eventually the standard model of particle physics. This progress and its technological applications commanded respect, if not outright fear.

But today, the foundations of physics are a sleepy place. We're still chewing on the same problems that we had a century ago—and all that chewing hasn't made them any more digestible. What is dark matter? What does quantum mechanics really mean? And why does gravity refuse to cooperate with quantum physics? These are problems that, when I can't sleep, I like to think have already kept Einstein up at night.

Since then, many ideas for solutions have been put forward for each of these problems, but it is rare for a truly new one to see the light of the day. This is why I was very excited to see the recent publications of Jonathan Oppenheim, a professor of quantum theory at University College London.

I have met Oppenheim a few times in the past because we share a similar intellectual history. Oppenheim and I both used to work on black holes, more specifically on the question of whether black holes truly destroy information. It seems that we both came to conclude the problem cannot be solved without first understanding how space, time, and quantum physics work together. But there, our ways parted. While I put the blame for the black hole information paradox on quantum physics, Oppenheim blamed gravity.

In all fairness, putting the blame on gravity makes more sense because gravity is the odd one out among the fundamental forces of nature. While electromagnetism (the union of the electric and magnetic force), the strong nuclear force (which keeps atomic nuclei together), and the weak nuclear force (responsible for nuclear decay) are all described by quantum processes, gravity is not.

Gravity is, as physics parlance has it, a "classical" or non-quantum theory, still described by Einstein's theory of general relativity. It is a deterministic theory, which means that future events can be deduced from past events. Quantum mechanics breaks with this determinism: It brings in an inherent randomness, unpredictable quantum jumps that happen whenever you measure a particle.

According to quantum mechanics, this randomness is fundamental; it is not due to our lack of information—it's just how nature is. As a consequence, with quantum mechanics we cannot make definite predictions, only probabilistic ones. We might be able to say, for example, that an atom decays with 50 percent probability within 10 days, but not exactly when it will decay.

Einstein did not like this at all. He thought that the randomness inherent in quantum mechanics just means that the theory is incomplete, that something is missing from it. A good theory, he believed, should be classical, like his own general relativity and, as Einstein quipped, if his theory was wrong, then he would be sorry for the good Lord.

So far, we have had no need to be sorry for the Lord. Einstein's masterwork has been tested countless times to utmost precision and held up to any attempt trying

PAGES 96-97: LIA KOLTYRINA / SHUTTERSTOCK

The idea is simple: Make gravity as random as quantum physics.

to falsify it. Empirical successes notwithstanding, most physicists think it is wrong. The reason is that general relativity cannot describe some situations that we know occur in nature.

TAKE A SIMPLE EXAMPLE that could happen in a laboratory right at this moment. An electron is sent through a plate with two thin slits, a double-slit. It's a particle with quantum properties, so the electron can go through both slits at the same time. This isn't just a story; we know that this is necessary to properly describe our observations on the screen behind the slit.

We also know that electrons have masses and that masses generate a gravitational pull. But if the electron goes through a double-slit, where is the gravitational pull directed? Einstein's general relativity cannot answer this question because it cannot deal with a particle that is in two places at the same time.

This is not the only situation with which Einstein's math can't cope. There is also the question of what happens inside black holes, that Oppenheim and I and many other physicists were trying to answer. A similar problem occurs with the Big Bang. Einstein's theory just isn't fit to deal with these cases. We need something better, a theory that combines quantum physics with gravity, usually called "quantum gravity."

Physicists had been discussing this problem already in the 1930s, around the same time that dark matter was first discovered. For decades, they thought that Einstein's gravity could be turned into a quantum theory, the same way physicists had done for the electromagnetic force.

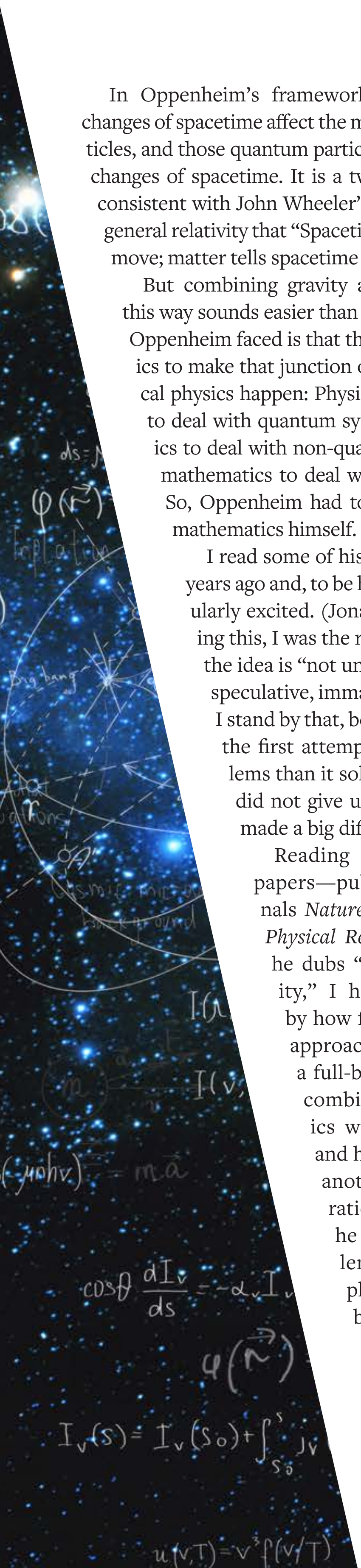
Come the 1960s, it turned out that this didn't work. Richard Feynman and Bryce DeWitt, among others, tried to give quantum properties to gravity using the already known mathematics. But the resulting theory (now known as "perturbatively quantized gravity") did not work. When extrapolated to extreme situations like the Big Bang or the inside of black holes—exactly the places that we are most interested in!—it produced incurable infinities. Those led to predictions of probabilities larger than one, useless mathematical nonsense that didn't help physicists understand what was really happening.

After that, there were many other attempts to turn gravity into a theory of quantum gravity: string theory, loop quantum gravity, asymptotically safe gravity, causal dynamical triangulations, and some more. They all have their pros and cons, but to make a long story short, their cons have prevented them all from being convincing (to anyone but the people who work on them).

If the past 50 years have taught us one thing, it's that the problem of reconciling quantum physics with gravity is much more difficult than anyone thought it would be. After so much trial and failure, it certainly seems that we are missing something big.

OPPENHEIM'S NEW THEORY could be what physicists have been missing. His idea is, on the face of it, quite simple: Rather than trying to give quantum properties to gravity, just make gravity as random as quantum physics, so that the two fit together.

Loosely speaking, Oppenheim postulates that space and time, combined to spacetime, constantly make small random changes. According to this theory, spacetime constantly shifts imperceptibly around us. This shifting—not to be confused with the wiggling of gravitational waves—ties together with gravity because in Einstein's theory, gravity is described by the curvature of spacetime itself.



In Oppenheim's framework, then, the random changes of spacetime affect the motion of quantum particles, and those quantum particles in return affect the changes of spacetime. It is a two-way process neatly consistent with John Wheeler's one-line summary of general relativity that "Spacetime tells matter how to move; matter tells spacetime how to curve."

But combining gravity and quantum physics this way sounds easier than it is. The problem that Oppenheim faced is that there was no mathematics to make that junction of quantum and classical physics happen: Physicists had mathematics to deal with quantum systems, and mathematics to deal with non-quantum systems, but no mathematics to deal with a mixture of both. So, Oppenheim had to go and develop that mathematics himself.

I read some of his early work about five years ago and, to be honest, I wasn't particularly excited. (Jonathan, if you are reading this, I was the referee who wrote that the idea is "not uninteresting" but "very speculative, immature, and vague." And I stand by that, because really I felt that the first attempt created more problems than it solved.) But Oppenheim did not give up, and five years have made a big difference.

Reading Oppenheim's new papers—published in the journals *Nature Communications* and *Physical Review X*—about what he dubs "Post-Quantum Gravity," I have been impressed by how far he has pushed the approach. He has developed a full-blown framework that combines quantum physics with classical physics, and he tells me that he has another paper in preparation which shows that he can solve the problem of infinites that plague the Big Bang and black holes.

IT IS WORTHWHILE to mention that Oppenheim's theory has close mathematical relatives in the foundations of quantum mechanics.

The standard formalism of quantum mechanics brings in the random element suddenly, in the moment when a measurement in a quantum experiment happens. Prior to a measurement, a quantum system can have many possible outcomes, but once a measurement has been made, these possibilities "collapse" to one actuality.

Say you send a quantum of light, a photon, through a semi-transparent plate known as a beam-splitter. According to quantum mechanics, what happens is not that half of the photons go through and the other half are reflected, but all photons split into both possibilities. Yet, once you measure whether the photon went through or didn't, you either detect it or you don't. So the two possibilities have collapsed to one.

In quantum mechanics, this collapse is a discontinuous and also faster-than-light process, which is difficult to reconcile with Einstein's ideas about how nothing travels faster than light. The reason the faster-than-light proceedings of the measurement collapse do not cause outright problems with Einstein's mathematics is that the collapse is not observable. This is because the only thing you observe is the outcome of the measurement—that is, the aftermath of the collapse—and not what happened before it. But it being not observable also means that we cannot know that it is truly discontinuous. And that opens the possibility to try and replace it with something better, something more compatible with Einstein's ideas.

One approach to this has been to remedy this sudden measurement collapse by turning it into a gradual process. This idea has been pursued in what has been collectively called "objective collapse models." In these models, a particle does not make one big random jump to one "actuality" at the time of measurement, but many small adjustments that add up to what we call the collapse. Oppenheim's approach mimics this idea, but also links it to gravity as the cause of those random jumps. It is gravity that mixes in the non-quantum element that takes over at the end of the measurement process.

That gravity is the cause of the measurement collapse by itself is an idea that was pioneered by Roger Penrose. Now, Penrose's approach works completely differently than Oppenheim's but still they are related

If the theory is right, Einstein is wrong. God does indeed play dice.

in that it is ultimately gravity which is responsible for the apparent collapse of quantum possibilities.

Oppenheim's post-quantum gravity changes both gravity and quantum physics. This is good news because it is extremely difficult to experimentally test changes to the law of gravity that concern quantum particles, because gravity is such an extremely weak force on small scales compared to the other fundamental forces. However, it is much easier to experimentally test deviations from quantum mechanics because those can be measured very precisely with new quantum technologies, and that opens a way to find out whether Oppenheim's idea holds up.

Models in which gravity is not a quantum theory generally tend to increase the uncertainty inherent in quantum physics. This might sound somewhat counterintuitive because quantum physics is known for its uncertainty, so one might think that leaving gravity a non-quantum theory would reduce this uncertainty rather than increasing it. Alas, leaving gravity non-quantum means that it doesn't fit to the quantum properties which we know particles to have—like being in two places at the same time. Making the two fit together then amplifies the randomness of quantum physics. In practice this can lead to an increase in jittering, or an unexpectedly large spread of measurement results.

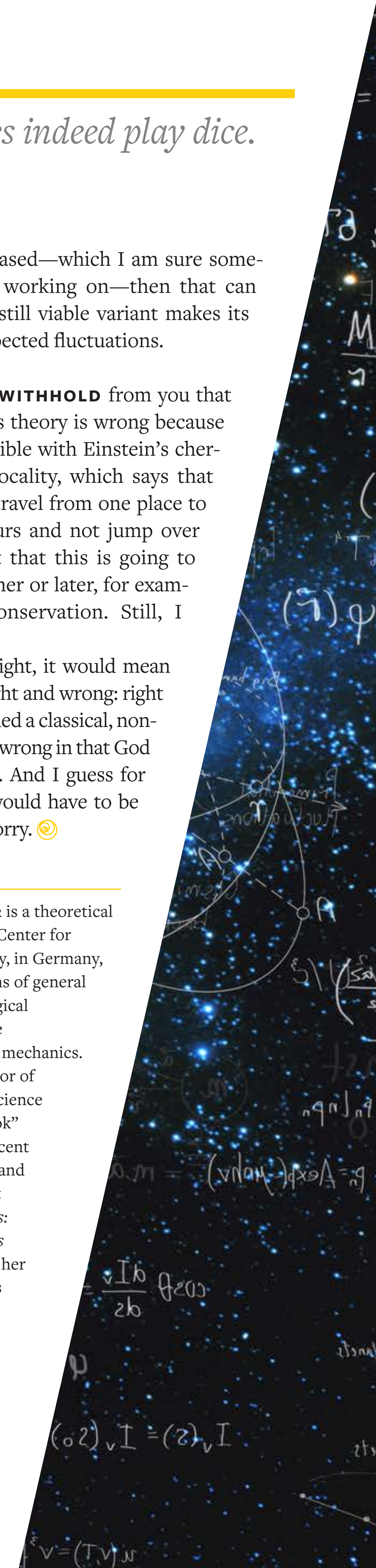
This amplification of quantum uncertainty also happens in Oppenheim's model. In this case, the origin is easy to pinpoint: The additional uncertainty comes from the postulated randomness of spacetime. This opens the possibility to experimentally test it, for example by precisely tracking the gravitational pull of objects and see if it unexpectedly fluctuates.

This can be done, for example, by a standard (Cavendish-type) experiment that measures the gravitational attraction between two objects by suspending them from wires and tracking how much the wires drill as the objects attract each other. The current experiments of this type rule out one variant of the post-quantum model, and if the sensitivity of experiments can be further increased—which I am sure someone, somewhere is working on—then that can tell us whether the still viable variant makes its appearance in unexpected fluctuations.

I DON'T WANT TO WITHHOLD from you that I think Oppenheim's theory is wrong because it remains incompatible with Einstein's cherished principle of locality, which says that causes should only travel from one place to its nearest neighbours and not jump over distances. I suspect that this is going to cause problems sooner or later, for example with energy conservation. Still, I might be wrong.

If Oppenheim's right, it would mean Einstein was both right and wrong: right in that gravity remained a classical, non-quantum theory, and wrong in that God did play dice indeed. And I guess for the good Lord, we would have to be both sorry and not sorry.

SABINE HOSSENFELDER is a theoretical physicist at the Munich Center for Mathematical Philosophy, in Germany, focusing on modifications of general relativity, phenomenological quantum gravity, and the foundations of quantum mechanics. She is the creative director of the YouTube channel "Science without the gobbledygook" where she talks about recent scientific developments and debunks hype. Her latest book is *Existential Physics: A Scientist's Guide to Life's Biggest Questions*. Follow her on X (formerly known as Twitter) @skdh.

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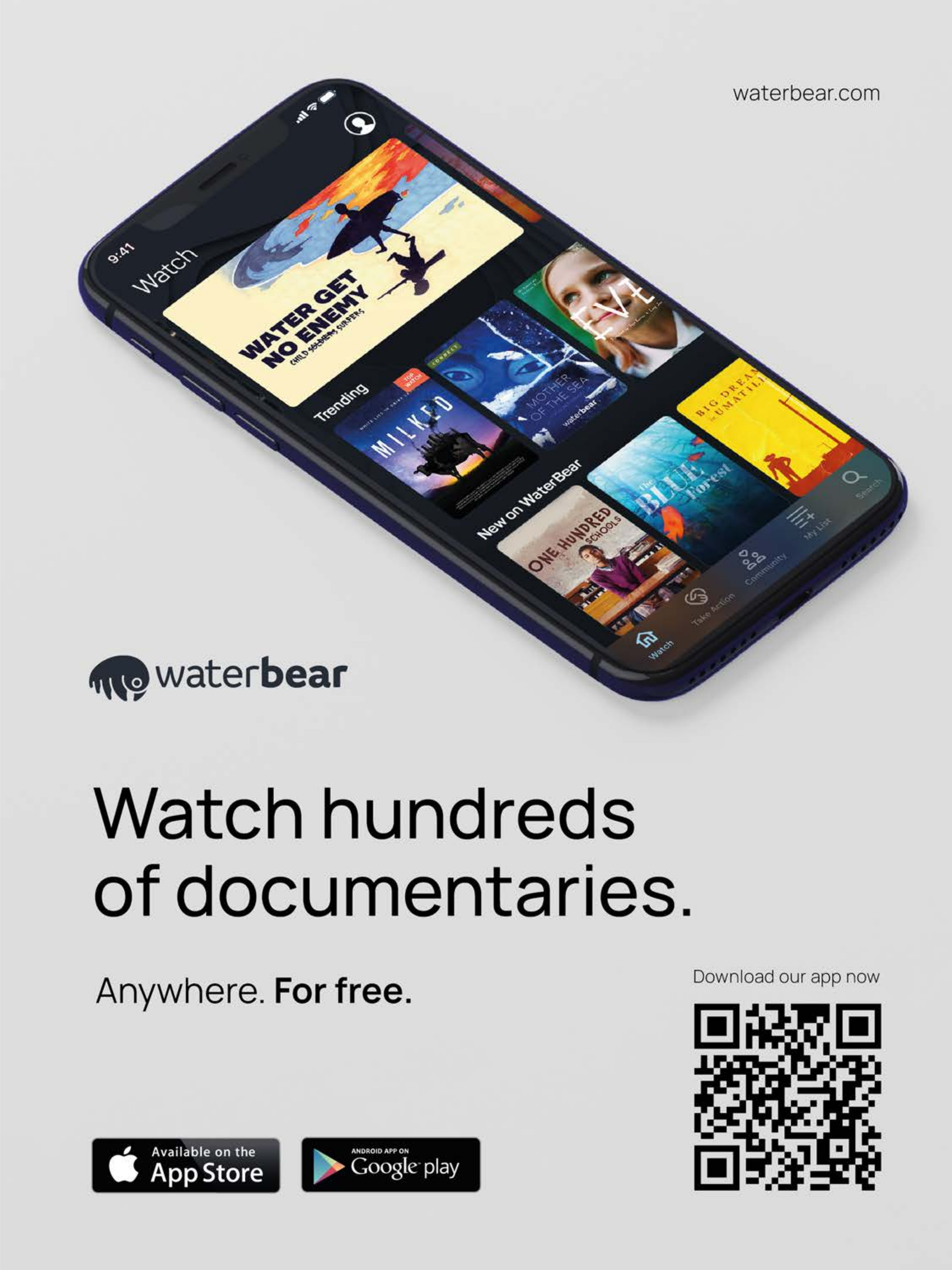
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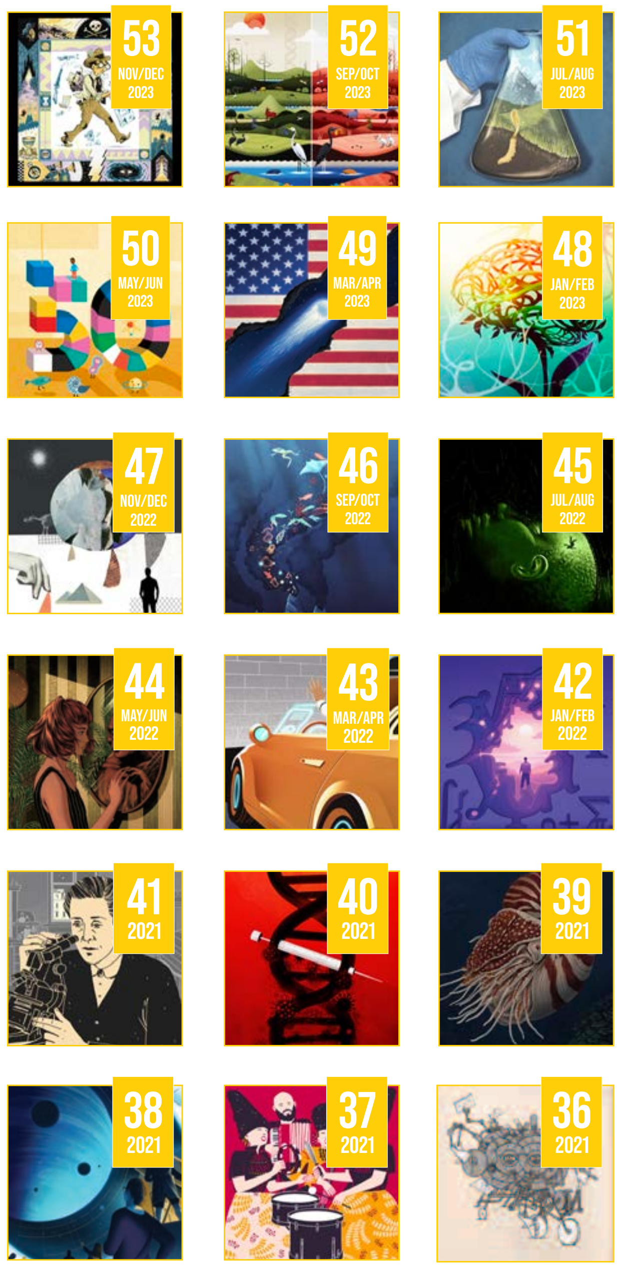

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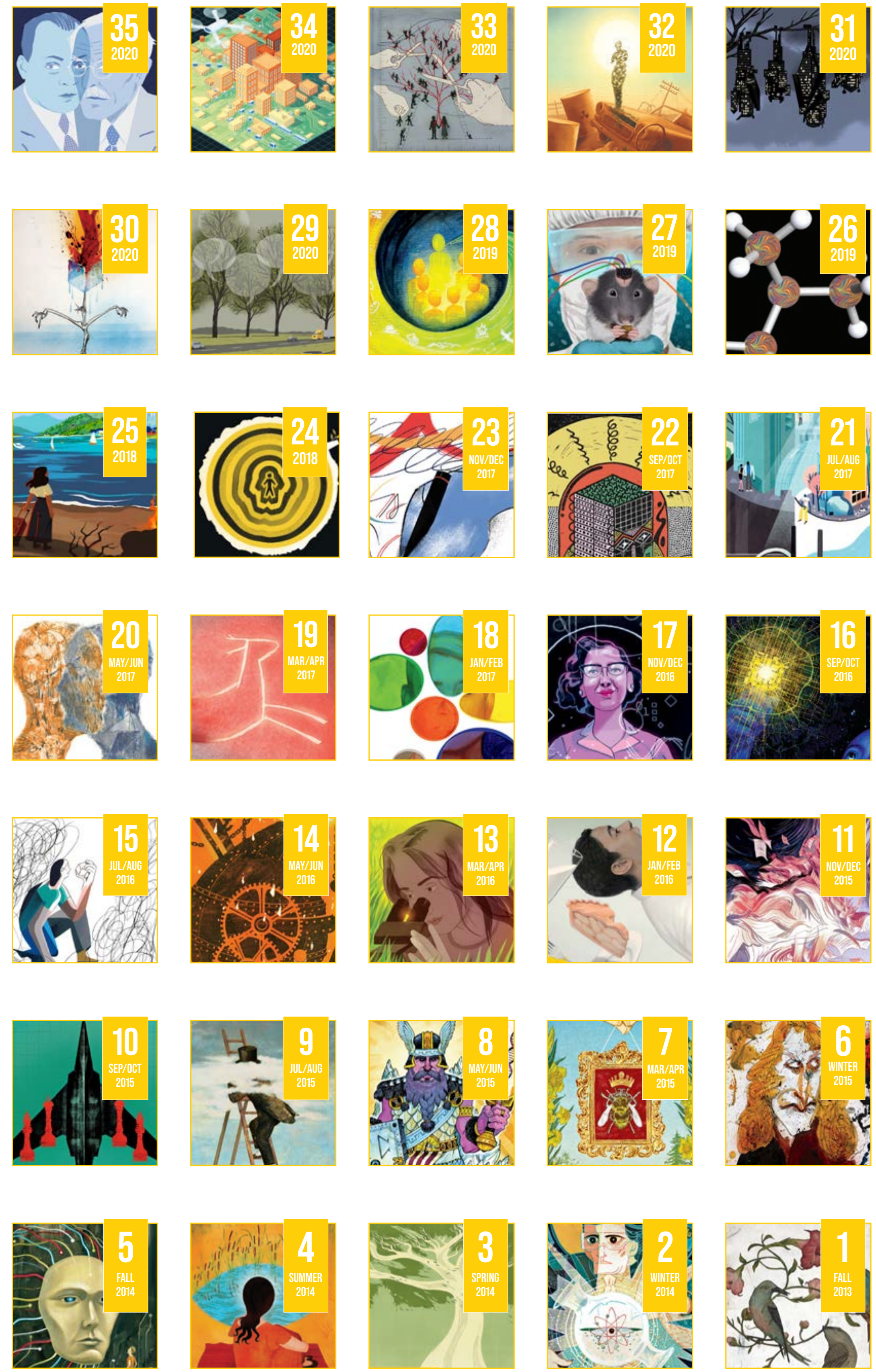

MY 3 GREATEST REVELATIONS

With the Apollo Missions, We Became Like Gods

What Rebecca Boyle learned while writing Our Moon, *about the power of our satellite to guide evolution and human curiosity*

BY REBECCA BOYLE

1

THE MOON AFFECTS LIFE IN PROFOUND WAYS

The moon may have dragged backboned animals out of the sea and onto the land, where they evolved into everything that has ever walked on Earth. Working with paleontologists and physicists, an oceanography graduate student determined that at a time when the moon was closer, 380-320 million years ago, it was driving very high tides—at the same time the supercontinent Pangea was forming. Tides would rise and fall by some 80 feet in just a few hours. The water rushed in and out so quickly that some fish were inevitably stranded. Fossils of bony fish from this era show a transition between water-dwelling animals and land-dwelling animals. So it looks like the moon probably played a major role in bringing our ancestors out of the sea.

2

RELIGION AND SCIENCE ARE CONNECTED MORE STRONGLY THAN YOU THINK

I have been trained, as a science journalist, to think that science and religion are two very distinct ways of observing the universe—one based on empiricism and one based on the lack of it. But I now think that empiricism itself, the idea of sense-based, evidentiary research, is derived from the earliest projects of human devotion. The Moon God was an important deity in many cultures throughout ancient Mesopotamia. Astrologers through the millennia, from the Sumerians to the Assyrians to the Babylonians, were tasked with studying the moon for spiritual purposes, including to predict future events and conduct rituals. Over time, their observations served as a record of scientific data, which was used by the Greeks and the Persians to deduce information about the universe.

I think the process of science—as conceived of in classical Greece and which flowered during the European Enlightenment—is actually derived from the spiritual need to understand the cosmos and our place in it. I think religion paves the way for science. They are both forms of informed worship, as Carl Sagan once wrote.

3

APOLLO WAS A SPIRITUAL EXPERIENCE

I came to think of the Apollo missions as neither a scientific undertaking nor even a geopolitical one. I think Apollo was more like a modern form of religious worship. The language used to describe the project was often accented with spirituality, I think because it was truly a transcendental event. We literally crossed the boundary of heaven and went to another world. It is a distant memory now, so it's easy to forget how truly awesome it was. Humans left Earth and walked around on another world.

I felt the profound strangeness of the moon landings after I saw the moon rocks myself. I was awed, chilled, and exalted by the presence of these rocks, which were so obviously not from Earth, but from another realm. I came to see the Apollo missions as marking the dawn of a new era, where the Earth became just one planet and humanity ourselves became like gods. We brought the moon down to Earth, and the Earth down to size.

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