SEPTEMBER 2022
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Forecasting Atmospheric Rivers

Saving Snakes with Social Media

Can an AI Write a Research Paper about Itself?

BLACK HOLE MYSTERIES SOLVED

INSIDE

HOW WORMHOLES RESOLVE A PARADOX

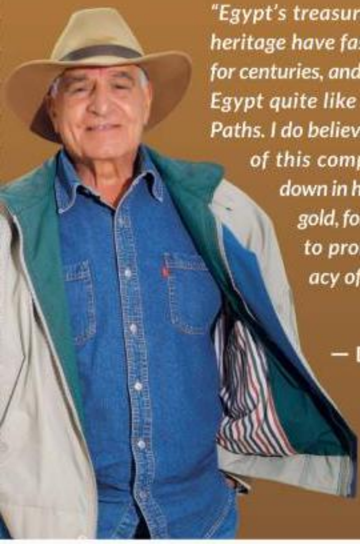
THE EDGE OF SPACE AND TIME

OUR BLACK HOLE REVEALED

EGYPT'S HIDDEN TREASURES

ARCHAEOLOGICAL PATHS

WHAT WILL YOU EXPERIENCE WHEN TRAVELING WITH ARCHAEOLOGICAL PATHS?



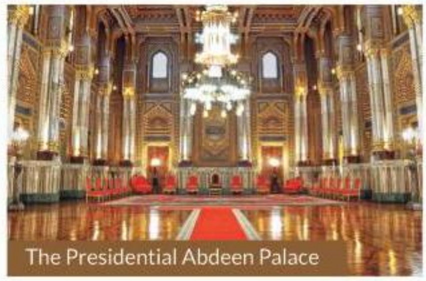
"Egypt's treasures and cultural heritage have fascinated people for centuries, and no one can tour Egypt quite like Archaeological Paths. I do believe that the name of this company should go down in history, written in gold, for its contribution to promoting the legacy of ancient Egypt."

— Dr. Zahi Hawass
the world's
most famous
archaeologist

For years, *Archaeological Paths*' exclusive historical tours of Egypt have attracted travelers drawn to the country's ancient past. For many, cruising down the Nile, visiting the ancient tombs of the pharaohs, exploring the Pyramids of Giza, or marveling at the Great Sphinx are bucket-list items. But the challenge of fulfilling a much-longed-for dream is that the experience must match – or better, exceed – expectations.

Archaeological Paths promises to completely change the way visitors explore the country as the company benefits from an unparalleled level of access. Archaeological Paths takes you where the general public can't go, in the company of the world's foremost archaeologists. And, in true royal style, all of this is paired with stays at former palaces, cruises on luxurious ships, and meals at the most exquisite local restaurants.

The Great Sphinx Enclosure



The Presidential Abdeen Palace

Now it's time to take a closer look at what makes these experiences extraordinary.
From Founder and CEO of *Archaeological Paths*, Grzegorz Popławski:

"At *Archaeological Paths*, our approach to luxury travel differs from other companies. We have changed the way the travel industry operates by offering unforgettable, unsurpassed, and unique experiences. Combined with our passion for history and exploration, this is one of the things that makes us distinct among tour companies.

Our guests have exclusive access to exceptional sites. Imagine Luxor Temple, the Valley of the Kings, or the entire Giza Plateau open just for you. For most visitors, a distant viewing platform is as close to the Great Sphinx as they'll get. With us, you can touch the Sphinx and stand between its paws as you watch the sunrise, a time when no one else is allowed at the site.

You can enjoy a VIP tour of the Grand Egyptian Museum or private entry to the Great Pyramid of Khufu, including a visit to the Queen's and Subterranean Chambers – both closed to the public. You'll have special access to 19th-century palaces that are official residences of the Egyptian president.

Archaeological Paths' guests are introduced to the latest discoveries at the Karnak Temple Complex

Another feature of our tours – not offered by any other company – is that we invite our guests to meet with individuals who shape history. Hearing from these knowledgeable experts is an experience like no other. These figures include the world's most famous archaeologist, **Dr. Zahi Hawass**, and Egypt's Secretary-General of the Supreme Council of Antiquities, **Dr. Mostafa Waziri**, presently responsible for all antiquities and archaeological sites in Egypt. There is no one better equipped to tell you about the most recent discoveries.

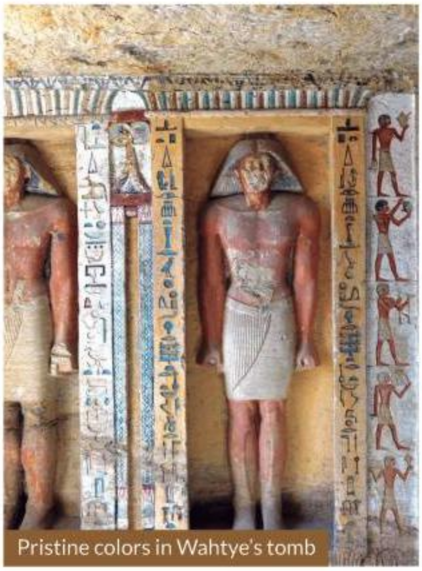
With us, you'll visit active excavation sites such as **Taposiris Magna**, the possible resting place of Cleopatra, the last queen of Egypt, or **the Tombs of the Pyramid Builders at Giza**. This site entirely changed the established understanding of how the pyramids were built. Imagine visiting this place in the company of the very person who discovered it, giving you unrivaled insight into Egypt's ancient past.

In addition to special access to some of the most iconic archaeological sites in Egypt already included in our tours' itineraries, there are always some surprises in store for our guests.

Dr. Mostafa Waziri shows the Temple of Khonsu, which is off-limits to the public

Taposiris Magna Temple

Tomb of Wahtye



Pristine colors in Wahtye's tomb

For example, in 2021, one of the best years for Egypt in terms of new archaeological discoveries, Dr. Hawass found the "**Lost Golden City" in Luxor**. This is now regarded as the second most important Egyptian archaeological discovery after Tutankhamun's tomb. Our guests were there before the discovery was even announced. Later that year, Egypt reopened **the Southern Tomb of King Djoser at Saqqara** after a 15-year renovation. Archaeological Paths' guests were in for a real treat as they enjoyed exclusive access to the site before its official opening.

And in December 2018, the **4,400-year-old tomb of Wahtye**, a high-ranking priest, was discovered at Saqqara. The vibrant colors in the tomb were almost pristine, which even archaeologists found surprising. The moment we learned that a new tomb had been found, we knew our guests had to witness it. That very day, our guests, along with Dr. Waziri and Dr. Hawass, explored this tomb. Since then, *Archaeological Paths* is one of the only companies allowed to lead its guests there. Imagine being one of the very few people in the world who have had the opportunity to enter this ancient burial chamber.

We may take you to a tomb that was discovered literally a few days earlier or a temple that will remain closed to tourists for years to come.

Don't be surprised, then, when you are a part of a similar experience during your tour. With us, you can expect the unexpected!

Opportunities like this make our itineraries the most exclusive and luxurious you can find. I always say that you might visit Egypt only once in your life, so you should have the richest experience possible and see things in the most intimate way. We want to create a trip filled with memories that will last a lifetime.

Whenever you hear about a new discovery in Egypt, we are there, together with our guests, providing the best access not only to ancient sites but also to all of **Egypt's hidden treasures.**"

Now you can be a part of *Archaeological Paths'* exclusive experiences! Book your tour today.

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Jeff Wilson (western diamondback rattlesnake)

SPECIAL REPORT

ON THE COVER
Black holes have posed some of the thorniest problems in physics, but recent research has made exciting progress. Scientists seem to be on their way toward resolving the so-called black hole information paradox, and the new insights may help us understand the cosmos as a whole. Astronomers have also taken the first photograph of the black hole at the center of the Milky Way.
Illustration by Olena Shmahalo.

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

New Solutions

If somebody yells, "Snake!" are you more likely to jump back in fright or say, "Ooh, where?" Fear of snakes (ophidiophobia) is one of the most common phobias: plenty of species are venomous, and in some religious traditions snakes are the embodiment of evil. It's no wonder they're unpopular. But advocates using social media are helping people identify and learn to live with snakes and even become fascinated with them. On page 54, author Emily Willingham introduces a cast of funny and charming converts who have gone from "Eek!" to "Ooh!"

One classic bit of writing advice is to use quotations to convey people's character or emotion. The "Saving Snakes" story does that beautifully, making the snake lovers seem so human and real, like people you just swapped stories with at a picnic. We get to know another kind of character on page 70, where researcher Almira Osmanovic Thunström shares a conversation she had with an artificial intelligence named GPT-3. She asked the AI to write up a scientific paper about itself, which raises all kinds of intriguing questions about scientific collaborations and publishing ethics and how easily we anthropomorphize AIs.

Weather forecasting has gotten steadily more accurate and farseeing over the past few decades, one of the many ways that science saves lives. On page 62, research meteorologist F. Martin Ralph discusses how he and his colleagues have come up with a new way to forecast and rate atmospheric rivers. These powerful storms form over the ocean and can be 2,000 miles long and 500 miles wide and cause devastating flooding, as happened in Yellowstone National Park earlier this year. The new atmospheric river scale may become as important and someday as well known as the Richter scale for earthquakes or the Saffir-Simpson scale for rating hurricanes.

Black holes have been a problem for physics for more than 60 years. They are so dense that their gravity permanently captures everything that comes near them, even light. As *Scientific American* contributing editor George Musser explains on page 30, this seems to violate a basic property of physics: that everything, in theory, is reversible and that information is never lost. Now physicists have come up with an explanation for how information can be preserved—or, actually, a few explanations. They disagree with one another (being physicists) on the details, but the solutions are all delightfully mind-bending and involve Hawking radiation, entangled quantum particles and wormholes (seriously).

Our special report on this exciting time in science includes a how-we-did-it story from physicist Ahmed Almheiri on page 34 describing how he and his colleagues arrived at an answer to the paradox. Physicist Edgar Shaghoulian on page 42 shows how the advances in understanding the edges of black holes have led to advances in understanding the edges of our universe. And a few months ago scientists revealed the first image of our very own black hole, Sagittarius A*, the black hole at the center of the Milky Way. Seth Fletcher, who runs *Scientific American*'s features department (and wrote a book about the search for Sgr A*), explores on page 48 what we've learned about it so far and what questions astronomers are working on now.

Space and physics editor Clara Moskowitz created the special package with a lot of enthusiasm from the rest of the staff. We hope you enjoy it and think about these stories of discovery next time you look up at the night sky. SA

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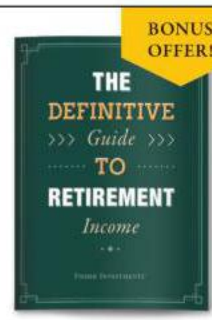

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May 2022

“Such an inspiring article on how there are places where humans have figured out how to integrate their society and culture with the ecosystem gives ecowarriors everywhere a little slice of hope that ecotopia *is* possible.”

ANGELIQUE KAMBEITZ *VICTORIA, BRITISH COLUMBIA*

QUANTUM NETWORK NEWS

In “Errors in the Machine,” Zaira Nazario discusses techniques to correct bugs in quantum computers faster than they can build up. As an early read-in mode (RIM) loader toggler of the PDP-5 minicomputer, which was designed for us at Chalk River Nuclear Laboratories in Ontario 60-odd years ago, I feel like I’ve stepped into Doctor Who’s time machine when reading Nazario’s beautiful presentation.

Along these lines, is it possible to separate the entangled qubits physically so that one has two entangled quantum computers? In such a case, this would seem to offer the chance for unhackable communications and navigation, both on Earth and in space. Indeed, if the entangled cohorts respond to each other in a dimension not limited by the speed of light, this could be the technology that eventually allows us to communicate with distant galactic neighbors.

JOHN LENG *Flagstaff, Ariz.*

NAZARIO REPLIES: Indeed, not only is it possible to have quantum processors physically separated and fully entangled functioning as one larger computer, but this is essential to scale to long-term, error-corrected quantum systems.

Modularity in a quantum system comes in different flavors. Take, for example, superconducting quantum computers. We will be able to parallelize them using classical communication as early as next year. We further envision having separate quantum chips linked inside a single cooling unit to allow gates between distant chips, effectively extending the chip size. We will have longer connections linking quantum processing units (QPUs) in separate cooling units inside a single system to remove bottlenecks in cooling and input/output for qubit control. This will also enable the nonplanar topologies that will allow us to implement more efficient error-correction codes. Finally, as Leng alludes to in his question, longer term, we will connect multiple quantum computers with distributed entanglement among them using technologies that convert the quantum-mechanical signals from microwave to optical frequencies and move them between distant dilution refrigerators via photonic links. At that point, we will have fully entangled clusters of quantum computers in a network resembling the intranet links in supercomputing processors.

This must be accompanied by modularity in software to give us “elastic” computing that quickly expands or decreases computer processing, memory and storage resources to meet demands in real time. Furthermore, run times will weave together QPUs, CPUs (central processing units), GPUs (graphics processing units) and other artificial-intelligence accelerators into a powerful computing fabric that integrates classical and quantum computations, including AI, to speed up the solution of some of the most pressing problems we face as scientists, members of society and business leaders. This computing fabric will be available to anyone in a seamless way, extending through multiple clouds, so that the complexities of the operation or orchestration happening behind the scenes are invisible to them.

Yes, this type of networking could have important implications for computation, communications and navigation. I don’t expect quantum networks to beat the speed of light, however.

LIVING WITH NATURE

“Designing for Life,” by Carolina Schneider Comandulli, with the Apiwtxa Association, describes lessons in sustainable living from the Indigenous Apiwtxa community in the Amazon basin. I must congratulate the authors on writing such an inspiring article on how there are places that still exist on Earth where humans have figured out how to integrate their society and culture with the ecosystem where they live. It gives ecowarriors everywhere a little slice of hope that ecotopia *is* possible. I thank the authors for writing it, the editors for including it and Earth for existing right now the way it does so that I was able to read and learn of this culture and place.

ANGELIQUE KAMBEITZ
Victoria, British Columbia

BARRIER TO ALZHEIMER’S?

In “Holes in the Shield” [May 2021], Daniela Kaufer and Alon Friedman explain how damage to the blood-brain barrier (BBB) may lead to Alzheimer’s disease and how animal studies indicate that repairs can make older brains appear young. Because the BBB loses effectiveness in advancing age, the authors note that they have a personal motivation for learning more about it, both being about 50. High levels of stress can cause defects in this important protective filter, and stress is something that an individual can reduce through changes in lifestyle. I hope that the authors or other researchers look into additional ways to protect the BBB that are within the individual’s control, such as diet modification, vitamin supplementation and exercise.

STEVE JONES *Henderson, Nev.*

Kaufer and Friedman describe experiments on mice showing that as the brain ages, the BBB becomes increasingly leaky to substances associated with inflammation and Alzheimer's. And the authors' use of tracer molecules in a study of humans in their mid-20s to mid-70s showed that BBB leakage also increased with age in people. The experiments did not fully prove that a damaged barrier causes Alzheimer's, however.

A noninvasive, ethically acceptable experiment that may help provide conclusive evidence of the role of BBB damage in Alzheimer's might be the following: Using a radioactive tracer, assess for BBB damage in ethnically and racially diverse populations of mentally healthy centenarians. If BBB damage is found in all humans with Alzheimer's, but such damage is absent in cohorts of the oldest mentally healthy humans (or present to no greater extent than it is in a healthy young population), would that not satisfy a criterion for causality?

MARK P. SILVERMAN *G. A. Jarvis Professor of Physics, Trinity College*

PROBLEMATIC PUNISHMENT

In imploring national leaders to take on racist-driven violence in the U.S. in "Stop Domestic Terrorism" [Science Agenda; April 2021], the editors emphasize, "Building on these steps, we can make it clear that homegrown terror and bigotry are real crimes. With real punishments."

That last word, "punishments," in this otherwise necessary editorial left me a little unsettled. I would have preferred "remedies" or similar from a science-based piece. Too often we go back to our religious habit of punishing unwanted behavior instead of finding better ways to counter it.

D. CLOUGH *via e-mail*

ERRATA

"Bold Experiments in Fish Farming," by Ellen Ruppel Shell, should have said that the system of the proposed major tank facility in Belfast, Me., currently circulates a total of 5,500 gallons of water a minute, not 5,200 gallons.

"Voyagers to the Stars," by Tim Folger [July], should have described NASA shutting down heaters and other nonessential components of the Voyager spacecraft over the past three years, not planning to turn off some of their systems this year.

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Health Care Starts at School

School-based clinics can reach kids who lack access

By the Editors

After more than two years of disrupted lessons during the pandemic, it's clearer than ever that schools are more than just places to learn: they are vital safe spaces for students to build friendships, receive nourishing meals and talk to trusted adults. And they can be more—schools can also provide health care.

Around 3,000 school-based health centers operate in more than 30 states all around the U.S., offering primary and preventive care for students who live in medically underserved areas. Staff at the centers treat flu, asthma, diabetes and other common ailments. They administer vaccinations and screen for dental, vision and hearing problems, and some provide mental health care and reproductive health care. These clinics, which are often partnerships between school districts and local community health organizations and hospitals, bring services to children who need them most and who have the greatest risk of falling behind in school because their health needs go unmet.

The pandemic was hard on existing school-based health centers, and as we reckon with lost years of education, it's time for government at all levels to recognize that all children need accessible and affordable health care. As lawmakers draw up budgets, reallocate funds and begin a new school year, existing clinics should be able to operate without budgetary fears, more dollars should go to school-based clinics, and more community partners should participate financially and physically in efforts to bring health care to the kids who lack it.

"Healthy kids learn better," says Robert Boyd, president and CEO of the School-Based Heath Alliance (SBHA), a nonprofit that promotes health centers in schools. More than 20 million children in the U.S. lack sufficient access to health care, and the most direct way to address that need is to bring doctors to them. "Many of their parents are unable to get away from work to take them to appointments," Boyd says. "And even if they are able to get away from work, often the kids miss a whole day of school. By having the health center right there in the school facility, they can do what they need to do and get back to class." And schools are often among the most trusted institutions within communities, making it easier to reach students who are anxious about visiting doctors' offices or whose parents mistrust outside providers.

Delivering health care through schools has been shown to improve kids' physical well-being and educational outcomes. A 2005 study in the *Journal of Adolescent Health* found that after health centers opened in U.S. public schools, their students' risk of hospitalization for asthma went down 2.4-fold, and their trips to the emergency room for asthma decreased by 33.5 percent. Other studies have shown that clinics in schools can increase vaccination rates among students, reduce mental health problems and boost students' use of contraception. On the education front, kids who use such centers have improved attendance and grades, are more likely to be promoted to the next grade and less likely to get suspended—and are overall more prepared for college. Based on all of this evidence, a Centers for Disease Control and Prevention task force recently recommended school-based health centers as a key strategy to advance health equity—that is, to reduce the access disparities that exist between wealthier, privileged populations and everyone else.

Yet most school communities that could desperately use such clinics lack them. In 2021 Congress appropriated $5 million to support new and expanded services at school-based health centers. That money funded 25 facilities—yet the program got more than 300 applications. And fewer than half of U.S. states currently fund school health centers. Although the clinics can also bill Medicaid and insurance for students who have coverage, they need stable funding for operating expenses, including hiring well-trained staff.

Many existing centers had to close temporarily or permanently during the pandemic, and centers struggled to retain staff and funding. One bright spot is that more than 60 percent of the centers that responded to an SBHA survey began offering telehealth services between 2020 and 2021, broadening their reach. And many were able to administer COVID vaccines to populations that lacked access to the lifesaving shots. Getting kids the care they need where they need it has always made sense, and it's more urgent than ever. The time is right to expand school-based health centers to all underserved students. SA

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Illustration by Martin Gee

Mitch Prinstein is chief science officer of the American Psychological Association. **Kathleen A. Ethier** is director of adolescent and school health at the Centers for Disease Control and Prevention. The views expressed are those of the author and not of the CDC.

Protecting Kids' Mental Health

Methods for preventing crises exist but are poorly implemented

By Mitch Prinstein and Kathleen A. Ethier

Young people in the U.S. are experiencing a mental health crisis. Reports from the surgeon general, the American Academy of Pediatrics and the American Psychological Association highlight the catastrophe, with families and children trying to get a moment with overwhelmed counselors, psychologists or social workers.

Is this crisis caused by the pandemic? No. Those of us monitoring the health and well-being of youth know this storm began years ago. In 2022 we continue to fund a children's mental health system based on the needs of adult war veterans.

Scientific advances have identified effective school-based mental health practices, such as emotional-regulation training that teaches children how to cope with strong feelings, or screenings to detect mental health crises before they occur. These insights and practices have largely been ignored. Now is the time to act on them. Long-disproved theories of physical and mental health as being two independent systems have motivated the annual investment of billions in medical research and physician training, but staggeringly few resources are available to advance psychological science or a mental health workforce.

The need is clear. Data from the Centers for Disease Control and Prevention, where one of us (Ethier) is director of adolescent and school health, reveal that in 2009–2019, a remarkably high number of young people reported feeling severe emotional distress. Specifically, in 2019, 37 percent of high school students surveyed felt so sad and hopeless they couldn't participate in regular activities, and about one in five seriously considered or attempted suicide. Adolescent girls and youth who identified as lesbian, gay, bisexual or transgender or who were questioning their identity were overrepresented among those who considered or attempted suicide.

The CDC's Adolescent Behaviors and Experiences Survey, the first nationally representative survey of U.S. high school students during the pandemic, revealed that young people's lives were extremely disrupted. Almost a quarter of U.S. youth told us they experienced hunger; more than half had been emotionally abused by an adult in their homes. More than 60 percent of Asian students and more than half of Black students encountered racism. Emotional distress and suicidal thoughts and behaviors continued to worsen and were more significant among female and LGBTQ students.

The way forward can be found in science-based psychosocial approaches that one of us (Prinstein) and our psychologist colleagues have developed over recent decades. We have identified effective methods to prevent emotional or behavioral distress by teaching children skills to cope with stressors, develop healthy social relationships and spot depression warning signs. For instance, during the pandemic, students who felt connected to others in school were less likely to experience indicators of poor mental health, as well as suicide plans and attempts.

Before the pandemic, by 2018, 79 percent of high schools identified safe spaces for LGBTQ youth, 96 percent had antiharassment policies and 77 percent had inclusivity professional development for staff. Many schools also had inclusive, student-led clubs. Recent CDC research found that having such policies and practices improved mental health not only for LGBTQ students but for all young people. Similar results from antiracism programs make schools less toxic for historically marginalized youth and improve the health and well-being of all students.

These approaches are not controversial. Methods to increase connectedness include classroom-management techniques that reinforce attentive, cooperative and collaborative behaviors, reduce peer victimization, and help youth understand how others feel and behave. Psychological prevention strategies can teach youth how to less frequently blame themselves for harsh experiences, help peers feel valued and included, and consider adaptive and healthy responses, even when confronted with aggression.

These programs require a commitment to the science of behavior and the deployment of innovative initiatives. And they need resources—to deploy these prevention approaches at scale and among populations most at need. Failure to address this mental health crisis will result in not only the distress of millions of U.S. youth today but a change in the productivity, success and wellness of U.S. citizens at large as this generation matures. SA

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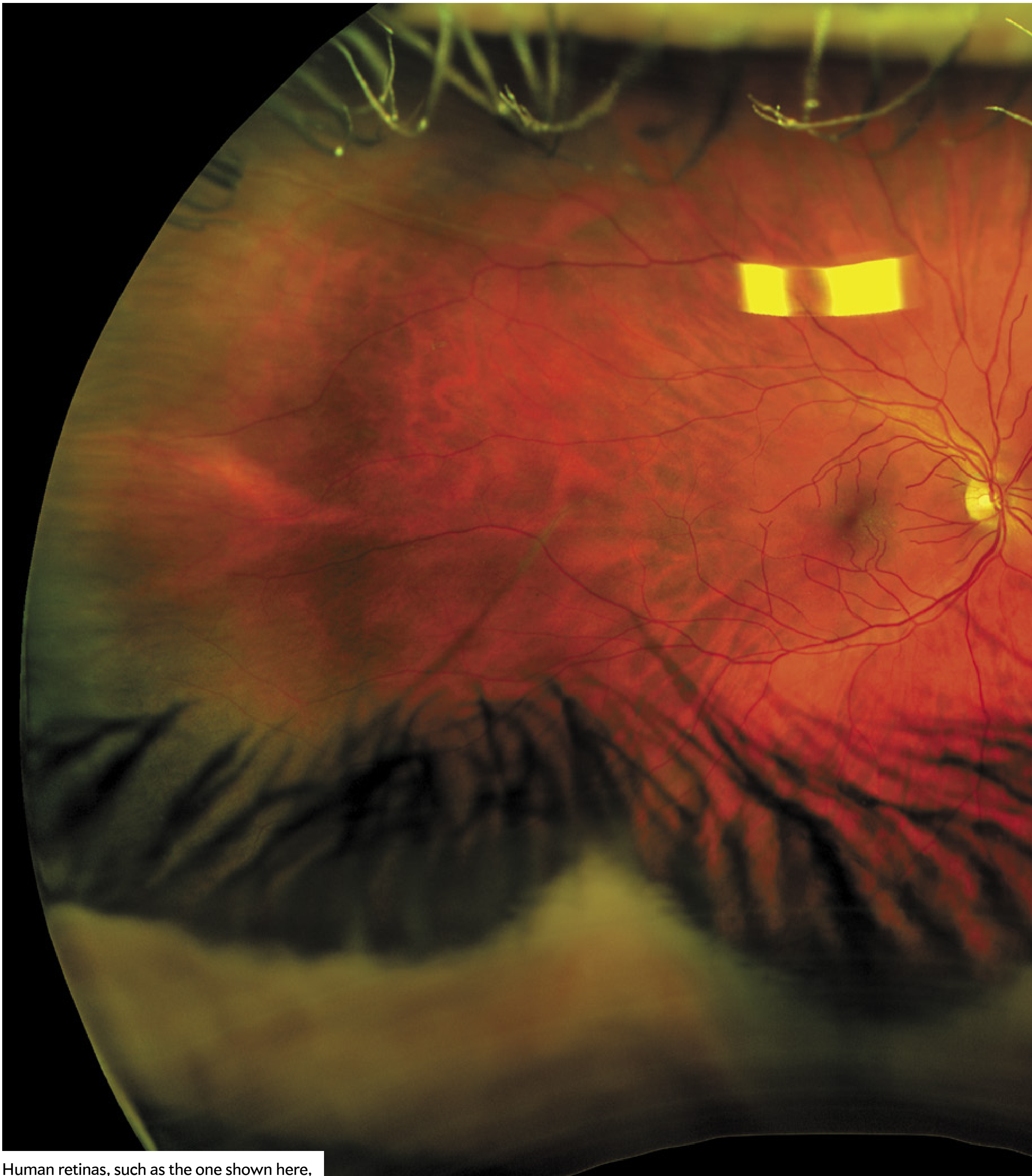
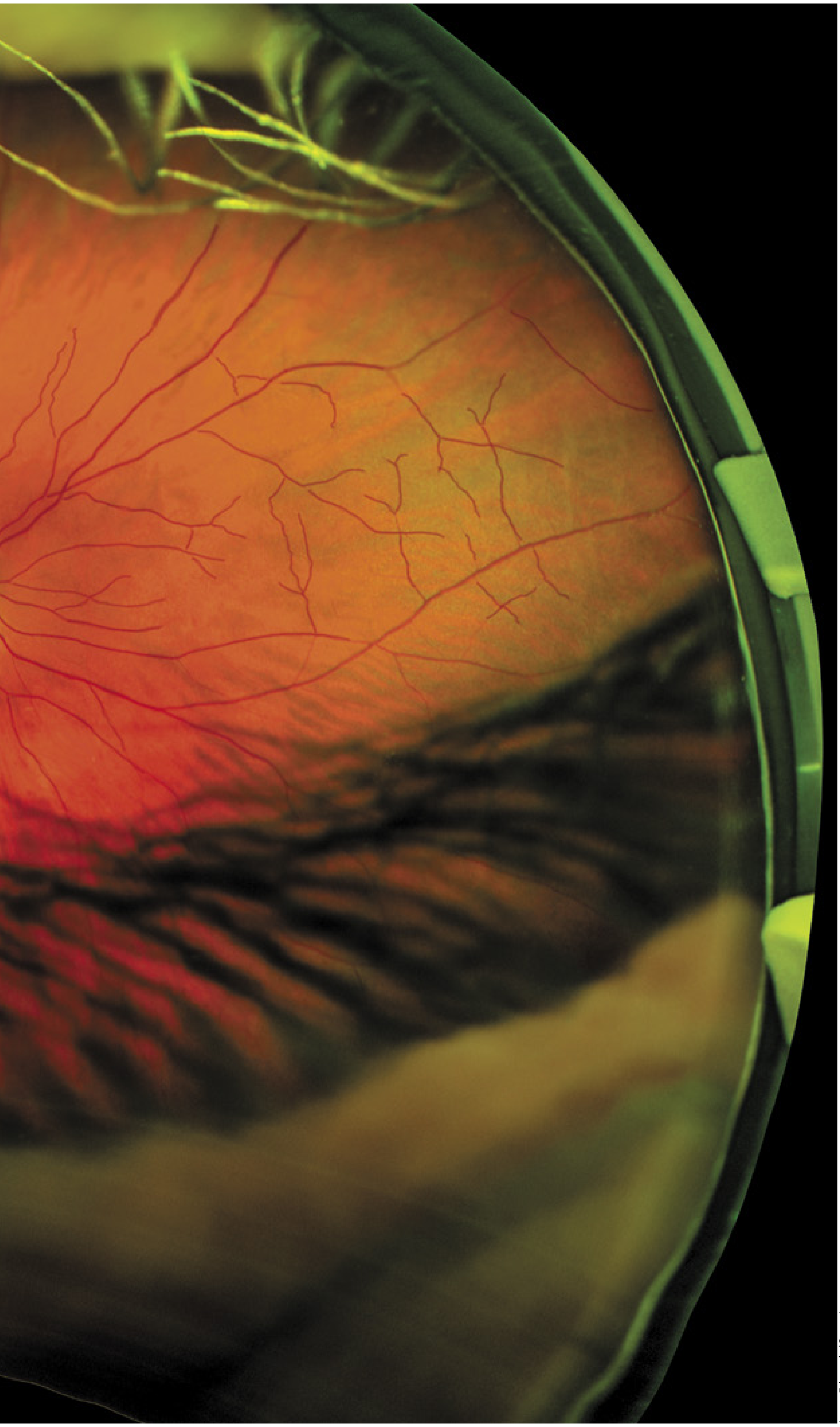
Illustration by Anson Chan

ADVANCES



Human retinas, such as the one shown here, may reveal signs of Alzheimer's disease.



Jason Edwards/Getty Images

HEALTH

Window to the Brain

Eye tests may help diagnose Alzheimer's disease

During an embryo's development, a piece of the still-growing brain branches off to form the retina, a sliver of tissue in the back of the eye. This makes the retina, which is composed of several layers of neurons, a piece of the central nervous system. As evidence builds that changes in the brain can manifest in this region, scientists are turning to retinas as a potential screening target for early signs of Alzheimer's, an incurable neurodegenerative disease that affects an estimated six million people in the U.S. alone.

Initially clinicians could diagnose Alzheimer's only through brain autopsies after patients died. Since the early 2000s, however, research advances have made it possible to pinpoint signs of the disease—and to begin to investigate treatment—years before symptoms first appear. Today positron emission tomography (PET) brain imaging and tests of cerebrospinal fluid (CSF), the clear liquid surrounding the brain and spinal cord, aid Alzheimer's diagnosis at its early stages.

"There have been tremendous improvements in our ability to detect early disease," says Peter J. Snyder, a neuropsychologist and neuroscientist at the University of Rhode Island. But these diagnostic methods are not always readily available, and they can be expensive and invasive. PET imaging requires injecting a radioactive tracer molecule into the bloodstream, and spinal fluid must be extracted with a needle inserted between vertebrae in the back. "We need ways of funneling the right high-risk individuals into the diagnostic process with low-cost screening tools that are noninvasive and simple to administer," Snyder says. The retina is a particularly attractive target, he adds, because it is closely related to brain tissue and can be examined noninvasively through the pupil, including with methods routinely used to check for eye diseases.

One approach to retinal screening aims to search for signs of beta-amyloid, the peptide that amasses into damaging plaques in the brains of people with Alzheimer's. Studies suggest this protein fragment also accumulates in the retina—and researchers have found evidence that it may be detectable there before the onset of symptoms.

In 2014 Robert Vince and Swati More of the University of Minnesota's Center for Drug Design first described how to use a method called hyperspectral imaging, which captures an image at many different light wavelengths, to identify amyloid aggregates (clumps of beta-amyloid) in mouse retinas. They then confirmed these clumps in the animals' brains at later stages of disease. Since first reporting those findings, the two scientists and their colleagues found that amyloid aggregates may act as an early marker in human eyes, too.

The team has since licensed the technique to a Canadian medical imaging company, RetiSpec, which combines it with a machine-learning algorithm that pinpoints amyloid clumps in hyperspectral images. Investigators at multiple facilities across North America are now conducting clinical trials to examine this technique's efficacy.

Preliminary findings from the trials, presented at a conference last November, included 108 participants who either were at risk of or had preclinical Alzheimer's or mild cognitive impairment, which can be an early sign of neurodegenerative disease. After comparing the retinal screening tests with PET and CSF results, the researchers found the technique correctly identified people with brain amyloid 86 percent of the time and correctly ruled out those without it 80 percent of the time. These results are promising, says Sharon Cohen, medical director at Toronto Memory Program and leader of the trial. More data are needed before this can be rolled out as an approved diagnostic tool, Cohen adds. "But I think that day will come."

Other researchers have also reported amyloid in the retinas of people whose PET scans show amyloid plaques but who do not show signs of cognitive decline. University of California, San Diego, neuroscientist Robert Rissman and his colleagues are conducting retinal screens in participants taking part in a larger, ongoing trial of an investigative Alzheimer's drug for this population. The investigators measured retinal amyloid in a small feasibility study of eight participants, and they are now screening retinas among a larger number of patients—both before and after treatment. These data may illuminate how retinal amyloid changes over time and show whether their treatment reduces its levels, Rissman says.

Scientists are also focusing on other retinal signs of early Alzheimer's. In a study published earlier this year in *JAMA Ophthalmology*, researchers reported that retinal thickness was associated with certain aspects of cognitive performance. And Snyder's team has been investigating progressive changes in the retina's anatomy, such as shrinkage in certain regions; preliminary work seems to indicate a correlation with amyloid buildup in the brain. Snyder and his colleagues are now looking for these and other retina-based biomarkers, such as changes in blood vessels, as part of a longitudinal trial known as the Atlas of Retinal Imaging in Alzheimer's Study (ARIAS).

Although there are a variety of approaches to retina-based diagnosis, Rissman says that they remain unproved at this stage. He cautions that there are several open questions—including whether the protein aggregates that researchers detect are actually amyloid. Snyder points out that scientists are still debating the best method of identifying the substance in retinas and that findings from imaging studies of these protein clumps have sometimes varied from one facility to another.

Cohen, however, says that "while additional confirmatory studies in different laboratories … are always welcome, there is sufficient evidence of amyloid deposition in the retina such that the finding should no longer be in dispute."

Early detection and accurate diagnosis are key to getting people on the right care and treatment path—and tools such as retinal imaging can aid both patients and physicians in that journey, says Rebecca Edelmayer, senior director of scientific engagement at the Alzheimer's Association. Even though the full potential of retinal imaging has yet to be determined, she adds, "it's a really interesting time in this space." —*Diana Kwon*

BIOLOGY

Propulsive Sting

Diving deep on sea creatures' extraordinary stingers

Jellyfish, sea anemones and corals, a group called cnidarians, sting with tiny, pressurized capsules that fire poisonous darts at explosive speeds. Researchers have been unsure of the exact mechanics of this blisteringly fast process, which occurs using special cell organelles called nematocysts. Now a team led by Matt Gibson and Ahmet Karabulut of the Stowers Institute for Medical Research in Kansas City, Mo., has used cutting-edge imaging technology to study nematocyst firing in very fine detail. Understanding the biophysics of what they call "one of nature's most exquisite biological micromachines" could inspire the design of minuscule drug-delivery devices, the researchers say.

This discovery, reported in *Nature Communications*, was aided by serendipity:

THEORETICAL CHEMISTRY

Quantum Mutants

Spooky physics could alter your DNA

Many biologists assume that bizarre quantum phenomena play a relatively negligible role inside the cell. A recent theoretical analysis of the chemical bonds holding DNA together, however, suggests that these effects might occur far more frequently than once thought—and act as a major source of genetic mutations.

Researchers led by Louie Slocombe of the University of Surrey in England focused on the molecular "bases" that make up the rungs linking DNA's double strands and the hydrogen bond, formed with a proton, that holds the two sides of these rungs together. Their theoretical model incorporated the quantum effects that allow a proton, bound to the base

Sea anemone

Robert Aguilar/Smithsonian Environmental Research Center (CC by 2.0)

Karabulut found that a chemical used to prepare sea anemone stinging cells for imaging also induced the nematocysts to discharge—and it fixed them, or preserved their cellular structure, at various stages in the process. Using super-resolution fluorescence and electron microscopes, the researchers observed a detailed sequence of events involving a stiff shaft and a flexible, whiplike filament that starts out coiled around it within the nematocyst.

Cells don't have space to operate a slingshot-type mechanism to propel a stinger, "so they evolved another way," Karabulut says. Both the shaft and the filament are inside out and neatly folded into the tiny organelle. When the nematocyst fires, the shaft is ejected first and turns right-side out. Then the filament unwinds and moves through the shaft, flipping right-side out as well. This flip turns the tiny, inward-facing barbs on the filament's surface outward to release toxins into unlucky prey.

Seeing this two-phase discharge process is "such a huge contribution to understanding the mechanics of turning this organelle inside out," says Cornell University evolutionary biologist Leslie Babonis, who was not involved in the study.

In the future, scientists could engineer "designer" cnidocytes to deliver drugs exactly where they are needed, Babonis says. "I don't think it's that far-fetched to think that this could be something that could be adapted or co-opted for use in medical systems or therapeutics."

—Viviane Callier

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cytosine on one strand, to spontaneously "tunnel" and hook up to the guanine base on the other.

Such an altered base pair, known as a tautomer, can quickly jump back to its original arrangement. But if the proton does not make it back by the time the two DNA strands separate—the first step of DNA replication—the cytosine might bind to a different base, adenine, rather than guanine. This unnatural pairing creates a mutation.

Scientists have known since the discovery of DNA's structure in the 1950s that base pairs can, in theory, produce tautomers. But they thought that quantum tunneling would have little relevance as a mutation generator because of the extraordinarily short lifetime of these physical states.

The researchers' model reported in *Communications Physics*, however, suggests that the quantum process happens so often that at any given time hundreds of thousands of tautomers may be present in a cell's genome. So even if these structures are fleeting, so many pop into place so frequently that they become a potentially rich source of mutations. This model suggests that quantum-mechanical instability "may well play a far more important role in DNA mutation than has hitherto been suggested," the authors write. The team wonders how specific repair mechanisms deal with such quantum errors, given that the predicted number of tautomers is thousands of times greater than the total number of mutations in each human generation.

This work could potentially "pave the way for investigating various quantum-tunneling processes in DNA and the cell membrane that may have fundamental importance in molecular biology," says Gizem Çelebi Torabfam, a scientist at Sabancı University Nanotechnology Research and Application Center in Istanbul, who has studied quantum tunneling but was not involved in this work. "Also, we should consider ultrafast transfer between two DNA bases in the pathogenesis of common diseases."

—Lars Fischer and Gary Stix

I'M SECULAR & I VOTE

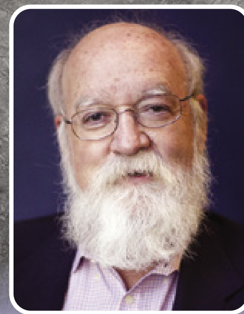

Photo by Brent Nicastro

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GENETICS

Color Cost

Cave fish trade their pigment for a thriftier metabolism

Mexican tetra, a blind cave fish

VPC Animals Photo/Alamy Stock Photo

Astyanax mexicanus cave fish have adapted to an incredibly tough environment: chilly, pitch-dark caves that flood about once a year, providing brief feasts separated by long periods of starvation. These fish put on fat easily, maintain high blood glucose levels and sleep very little. They also have lost their eyes and coloration. Despite the challenging conditions they live relatively long lives, often reaching 15 years. Now new genetic research shows that the loss of color, rather than being incidental to evolution, may actually help these hardy fish generate crucial energy.

Researchers at the Stowers Institute for Medical Research in Kansas City, Mo., led by evolutionary biologists Jaya Krishnan and Nicolas Rohner, discovered this possibility when mapping gene-regulation changes that help *A. mexicanus* survive its harsh environment. Studying regulatory regions of DNA (which do not produce proteins directly but instead control where and when other genes produce them) is challenging, and the scientists used two techniques to compare such segments in the cave fish with those in related river fish. First they mapped changes in chemical marks on the DNA that determine which genes are expressed, and then they tracked mutations in the regulatory regions—which they identified by looking at which segments of genetic code were physically opened for transcription and which ones were folded and closed.

"This represents a massive technological advance that will enable future [cave fish] studies," says Suzanne McGaugh, an

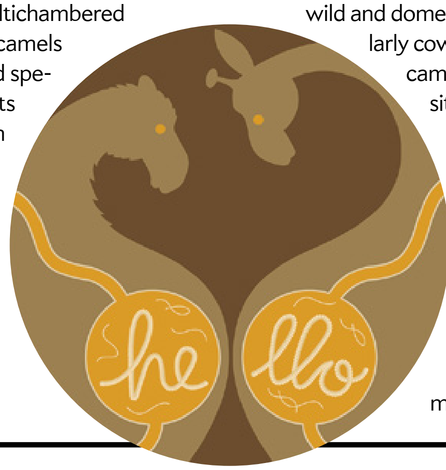
ECOLOGY

Gut Check

Poop patrol spies on parasites' secret world

If a goat and a hippo walk into a watering hole on the savanna, they could end up sharing a lot more than just a drink. Intestinal parasites, transmitted through water and food, can inflict damage ranging from stunted growth to starvation and death. To predict how these worms might spread in places such as central Kenya, where wild and domestic herbivores increasingly mingle, scientists are trying to get a better understanding of which parasites live in which species—and why.

A new study in the *Proceedings of the Royal Society B* shows that intestinal parasites are choosy about their living quarters; related parasite species tend to congregate in animals whose guts are alike. By chemically analyzing 550 fecal samples from 17 herbivore species, researchers identified snippets of parasite genes, called DNA barcodes, to catalogue the parasite populations likely to be living in the animals' guts. The 80 or so worm types they found seemed to be split between two different kinds of digestive systems. Some stuck to simple, single-chambered stomachs, and others preferred multichambered ones, like cows and camels have. Even unrelated species such as elephants and donkeys—which have little in common except for their single-chambered stomachs—had genetically similar parasites, suggesting these mammals might infect one another.



Knowing which worms live in whom helps farmers and conservation experts manage parasite spread. Many farmers in Kenya have recently swapped cows for drought-resistant livestock, including camels, in response to longer dry seasons. Although camels are genetically very different from their new savanna neighbors, they evidently share parasites with many wild and domestic animals—particularly cows. And 90 percent of camels sampled had parasites, compared with an average of 65 percent for other species sharing multichambered stomachs.

"We had no idea that camels were that infected and that they shared their parasites with so much of the wildlife,"

Illustrations by Thomas Fuchs

evolutionary biologist at the University of Minnesota, who was not involved in the new study, published recently in *Nature Genetics*.

Using these techniques, the researchers found many differences in the cave fish genomes compared with their surface fish relatives', including a deleted DNA segment in the gene *hpdb*. This mutation makes the cave fish unable to metabolize the amino acid tyrosine to make the pigment melanin, resulting in their colorless appearance. The researchers concluded that tyrosine "can [instead] get shuttled to make energy when the cave fish is already in an energy-deprived situation," Krishnan says. "It uses any or all available substrate to make energy and survive in that harsh environment."

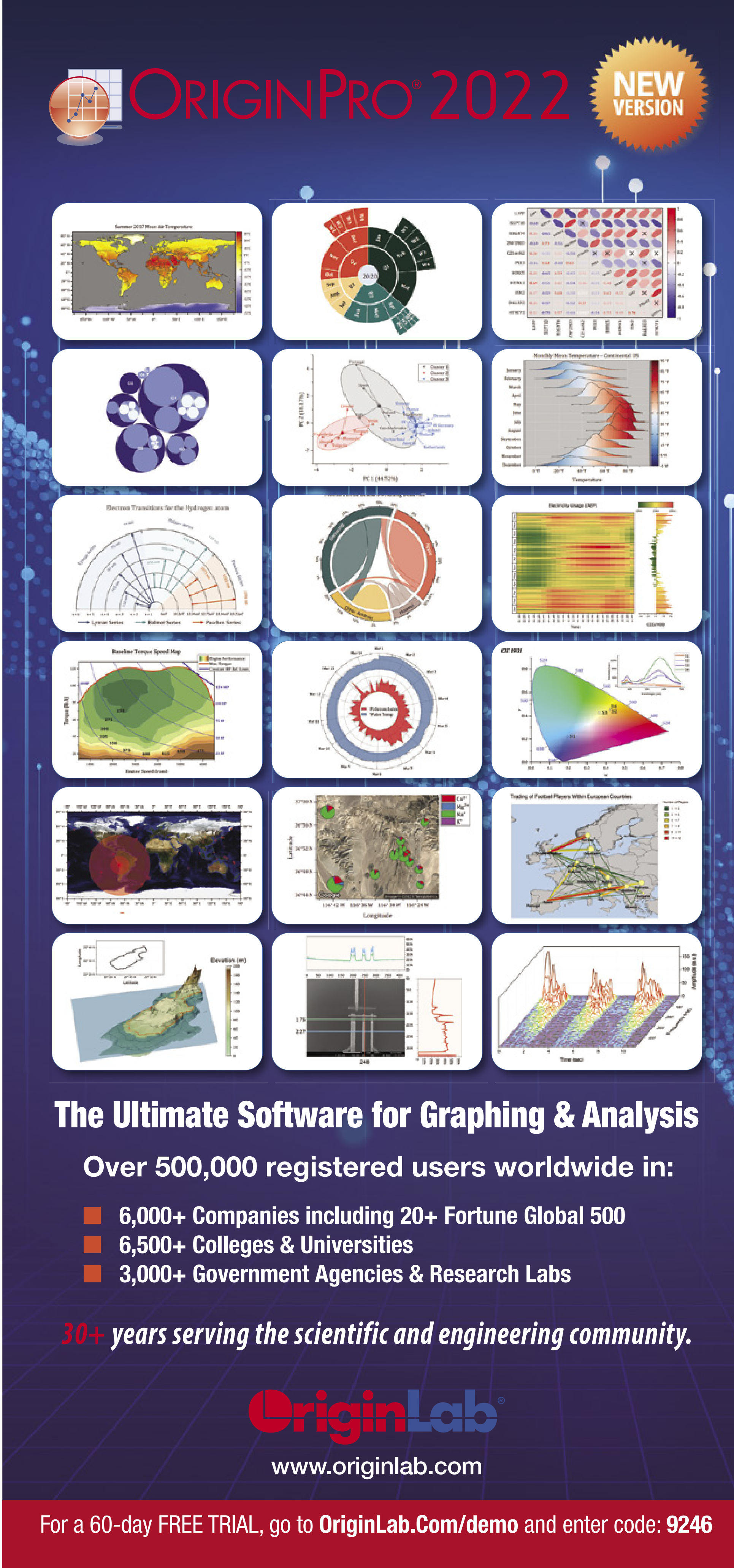
Tyrosine also helps to produce dopamine and norepinephrine, which many animals secrete in response to stress. Previous cave fish studies have connected pigment loss to increased levels of these hormones and to the cave fish's low sleep requirements. This paper suggests that loss of pigment affects metabolism as well, McGaugh says.

Because traits such as coloration, metabolism and sleep rely on related hormones and chemical reactions, adaptation in one area will alter all of the others, too. These trade-offs are likely the rule rather than the exception in animals that live in nutrient-deprived habitats, Krishnan says. —*Viviane Callier*

says the study's lead author Georgia Titcomb, a disease ecologist at the University of California, Santa Barbara. Based on her paper's results, local wildlife managers have decided to deworm camels in the study area to protect animals such as giraffes, whose numbers are declining.

To identify intestinal worms, most parasite researchers use slow, expensive processes such as culling animals or combing through feces under a microscope for parasite eggs. Without DNA barcodes, Titcomb and her team could not have gotten such a full picture of the parasite population.

"I do think that these are the perfect tools to ask exactly these kinds of questions, such as what determines the composition of parasite communities," says Sebastién Calvignac-Spencer, a disease ecologist at the Robert Koch Institute in Berlin, who was not involved in this work but uses DNA barcodes to study mammal viruses. Both researchers hope that this approach will gain traction among parasitologists. —*Sasha Warren*



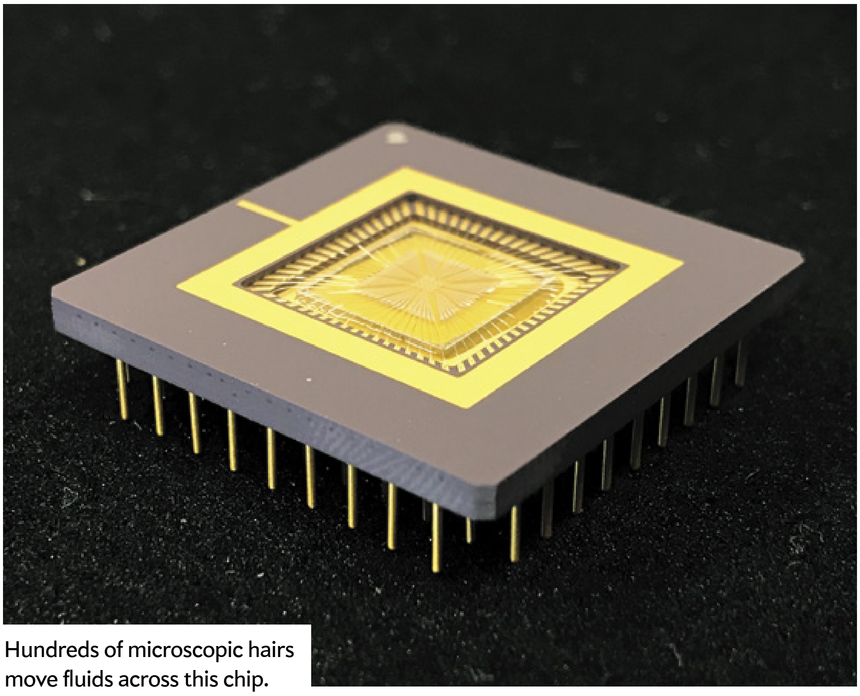
TECH

Micro Flow

Artificial cilia could aid portable medical diagnosis

One tiny flick of a microscopic cellular hair, known as a cilium, can't do much on its own. But together these structures routinely pull off biological marvels within the body. Cilia remove inhaled pathogens from the respiratory tract, carry cerebrospinal fluid across brain cavities, transport eggs from the ovary to the uterus, and drain mucus from the middle ear to the nasal cavity. Scientists have been trying for years to mimic these wonders of nature.

Now researchers have come closer to doing so, creating a chip covered with artificial cilia that can precisely control fluids' minuscule flow patterns. The developers hope this technology will become the basis of new portable diagnostic devices. A cilia-covered chip, the researchers say, could let researchers test blood, urine and other fluids to diagnose illness more efficiently than with laboratory-based tests—as well as using much smaller samples of testing material.



Hundreds of microscopic hairs move fluids across this chip.

Humans have achieved spectacular large-scale engineering feats, but "we are still kind of stuck when it comes to engineering miniaturized machines," says Cornell University physicist Itai Cohen, senior author of a new *Nature* study describing the cilia chip. Researchers had previously tried to make artificial cilia that can be moved using pressure, light, electricity and even magnets. But a major hurdle was designing extremely tiny actuators—the motion-triggering parts of a machine—that can be controlled individually or in small clusters rather than all at once.

In 2020 Guinness World Records recognized Cohen's team for designing the world's smallest walking robot, a machine just a fraction of a millimeter wide that could walk on four bendable legs. Much like those legs, the group's new artificial cilia are made of bendable, nanometer-thin film that responds to electrical control. Each cilium is one twentieth of a millimeter long (less than half the length of a dust mite) and 10 nanometers thick—slimmer than the smallest cell organelle—with a strip of platinum on one side and a coating of titanium film on the other.

The key to electrically controlling these artificial cilia comes from their metal makeup. Running a low positive voltage through a particular cilium triggers a chemical reaction: as a portion of test fluid flows past, the electrified platinum breaks apart the water molecules within the fluid. This frees up oxygen atoms, which are absorbed into the platinum's surface. The added oxygen stretches the strip, making it bend in one direction. Once the voltage is reversed, the oxygen is driven out of the platinum, and the cilium returns to its original shape. "So by oscillating the voltage back and forth, you can bend and unbend the strip, which will generate waves to drive the [test fluid's] movement," Cohen says. Meanwhile the electrically inert titanium film stabilizes the structure.

By simply bending and unbending one after the other, these fine strips can drive a microscopic amount of fluid in a set direction. The Cornell team's test chip, about a centimeter wide, hosts 64 arrays of eight tiny platinum-titanium cilia each, in which each array is independently controllable. This arrangement can set in motion nearly endless combinations of flow patterns. Next, the researchers hope to build a chip using cilia with more than one "hinge," boosting bending ability and the chip's efficiency.

The study "elegantly enlightened us about how independent, addressable control of artificial cilia arrays could be realized via electronic signals," says Zuankai Wang, a microfluidics researcher at the City University of Hong Kong, who was not involved in the study. "The mass production of untethered low-cost diagnostic devices could be within reach in the years to come." Such devices would use cilia to shuttle tiny samples of water, blood or urine from one spot to another to mix and react with various testing agents, searching for contaminants or markers of disease.

"It's superb how they have combined microelectronics with fluid mechanics," says Manoj Chaudhury, a materials scientist at Lehigh University, who was also not involved in the study. The researchers have solved an essential problem, but bringing a real-world testing system to fruition will require further work, Chaudhury says: "When they design a reactor system to analyze a drop of blood, there have to be local stations where they may even have to heat or cool the sample. So it would be interesting to see how they might integrate all these aspects in a micro reactor." —*Saugat Bolakhe*

Wei Wang and Qingkun Liu

IN THE NEWS

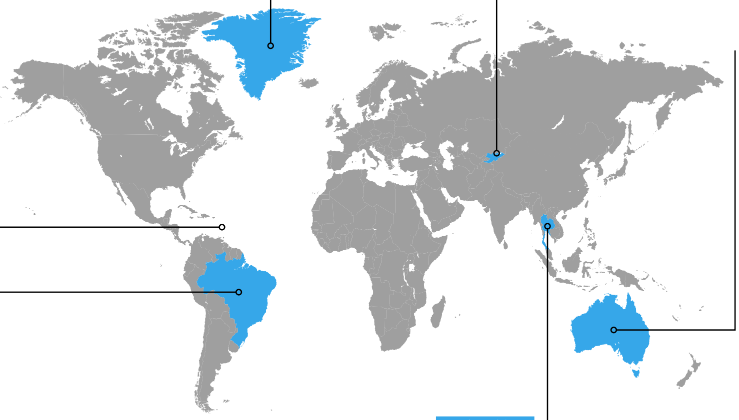
Quick Hits

By Fionna M. D. Samuels

For more details, visit www.ScientificAmerican.com/sep2022/advances

GREENLAND
Researchers found that an isolated polar bear population has adapted to thrive without long-term access to sea ice by hunting from fallen chunks of glacier ice instead. This skill could help them endure as the climate changes and sea ice dwindles.

KYRGYZSTAN
An ancestral strain of *Yersinia pestis*—the bacterium responsible for the Black Death—was sequenced from the teeth of two 14th-century women buried eight years before the plague spread across Europe. The strain's DNA was only two mutations shy of the one that caused the notorious disease.



GUADELOUPE
A newfound, centimeter-long bacterium challenges conventional wisdom that bacteria cannot grow large enough to be seen with the naked eye. Scientists wonder whether their sulfur-rich mangrove habitat is what lets these segmented single cells reach the size of an eyelash.

AUSTRALIA
Researchers suggest a 77-square-mile seagrass bed, once continuously connected by roots, is the world's largest-known organism. This hybrid of Poseidon's ribbon weed first sprouted 4,500 years ago and has since grown to dominate the floor of Shark Bay on the country's western coast.

BRAZIL
Scientists discovered that a tiny toad species' inner ears are too small to work as internal gyroscopes, leading to terrible jumping skills. The diminutive orange amphibians somersault through the air, often landing on their backs.

THAILAND
Reexamining ancient chicken bones revealed that the fowl were likely domesticated in Thailand about 3,500 years ago, thousands of years after previously proposed domestication dates. The birds may have been attracted to newly cultivated rice paddies.

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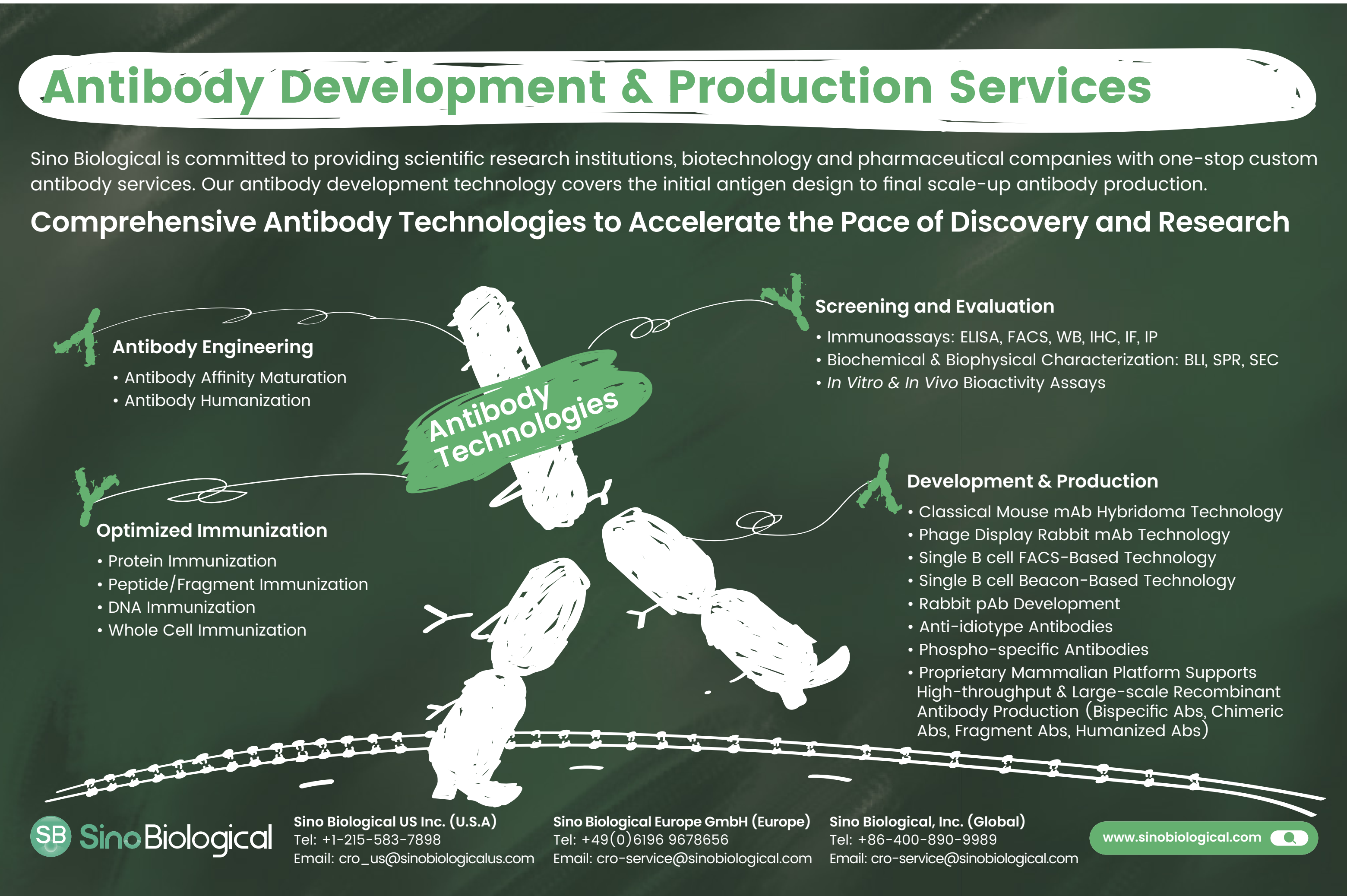


NEUROSCIENCE

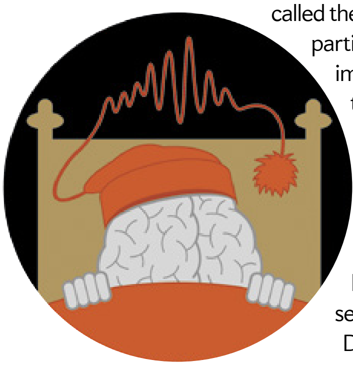
Memory Spikes

Signal in sleeping brains tied to acts of learning

Distinctive bursts of sleeping-brain activity, known as sleep spindles, have long been generally associated with strengthening recently formed memories. But new research has managed to link such surges to specific acts of learning while awake.

These electrical flurries, which can be observed as sharp spikes on an electroencephalogram (EEG), tend to happen in early sleep stages when brain activity is otherwise low. A study published in *Current Biology* shows that sleep spindles appear prominently in particular brain areas that had been active in study participants earlier, while they were awake and learning an assigned task. Stronger spindles in these areas correlated with better recall after sleep.

"We were able to link, within [each] participant, exactly the brain areas used for learning to spindle activity during sleep," says University of Oxford cognitive neuroscientist Bernhard Staresina, senior author on the study. Staresina, Marit Petzka of the University of Birmingham in England and their colleagues devised a set of tasks they called the "memory arena," which required each participant to memorize a sequence of images appearing inside a circle. While the subjects did so, researchers measured their brain activity with an EEG, which uses electrodes placed on the head. Participants then took a two-hour nap, after which they memorized a new image set—but then had to re-create the original image sequence learned before sleeping.



During naps, the researchers recorded stronger sleep spindles in the specific brain areas that had been active during the pre-sleep-memorization task, and these areas differed for each participant. This suggested that the spindle pattern was not "hardwired" in default parts of the human brain; rather it was tied to an individual's thought patterns. The researchers also observed that participants who experienced stronger sleep spindles in brain areas used during memorization did a better job re-creating the images' positions after the nap.

Previous research suggested spindles trigger brain changes that start the process of strengthening and refining a memory, in part by controlling the influx of calcium to certain cells. The new study is the first to directly measure brain activity during learning to support such a link and the first to associate better memory recall with stronger spindles in areas that had been active during learning, the researchers say—although they note it does not indicate whether spindles themselves actively improved recall. Staresina says that future work should examine spindle and other activity in the hippocampus, the brain's memory hub.

The study is "a convincing manuscript that supports the role of spindles in memory," says Lourdes DelRosso, a sleep researcher and physician at the University of Washington and Seattle Children's Hospital, who was not involved in the work. She hopes scientists also investigate spindles in people with conditions that affect learning and attention, such as ADHD and dyslexia. —*Rebecca Sohn*

Flying spider-monkey tree fern

BIOLOGY

Fern Tree of Life

Sequencing offers clues to a giant genetic mystery

Ferns are weird. They're green and leafy like other forest plants, but they reproduce more like mushrooms do—by releasing clouds of spores. Many species don't require a partner for fertilization, unlike most of their seed-bearing cousins. Recent studies estimate ferns split from seed-bearing plants about 400 million years ago.

And fern genomes are bafflingly large. Despite ferns' unique physiology and their relationship to seed plants, however, these strange genomes have been largely neglected by researchers. Until recently, only two (relatively small) fern genomes were fully sequenced, compared with more than 200 flowering plant genomes. Now the first full tree fern genome has been successfully sequenced—that of the flying spider-monkey tree fern—hinting at how these peculiar plants accrued such a massive set of genes.

"If you want to understand the origin of seeds or flowers, ferns are a very important comparison to make," says Fay-Wei Li, a fern biologist at the Boyce Thompson Institute at Cornell University and co-author on the new study, published in *Nature Plants*. "But what I really want to know is why the fern genomes are this damn big."

Li's team found that the palm tree–shaped fern has more than six billion DNA base pairs, a billion more than the average genome for flowering plants (humans, by comparison, have about three billion pairs). The new analysis suggests that more than 100 million years ago, an ancestor of this fern duplicated its whole genome—a replication error that is common in plants, Li says.

But it is not clear why tree ferns would keep so much genetic material; most flowering plants return to slimmer genomes after duplications. This species might be hoarding chromosomes, Li says: "I call this the Marie Kondo hypothesis. The chromosomes spark joy for ferns, but they don't spark joy for seed plants." For plants that reproduce asexually, he says, a large genome can add opportunities for beneficial mutations to occur while buffering from undesirable ones. Ferns are also long-lived, so they evolve more slowly, which may have contributed to the retained genetic material.

Using the fully sequenced genome, the researchers also found which genes build the fern's unusual trunklike stem—a valuable insight into how key traits evolved in stemmed plants, says Jan de Vries, a plant evolutionary biologist at the University of Göttingen in Germany, who was not involved in the study. "Evolution is a tinkerer. Illuminating what workable molecular programs have evolved tells us what is biologically possible and where the constraints are," he says. "Using this knowledge, we can start tinkering ourselves for synthetic biological purposes." —*Fionna M. D. Samuels*

Neil McAllister/Alamy Stock Photo

SEISMOLOGY

Icy Resonance

Ice sheets amplify hidden volcanic clues

Researchers rely on the rumble of magma moving underground to predict impending volcanic eruptions. But standard seismic tools provide only a rough picture of what's happening beneath Iceland's ice-covered volcanoes. ETH Zurich seismologist Andreas Fichtner and his colleagues recently showed how the same ice sheets that hide these volcanoes can amplify otherwise undetectable seismic signals.

Iceland's most active volcano, Grímsvötn, is entirely covered by Europe's largest glacier. In recent history it has erupted explosively about once per decade, generating flood hazards and dangerous ash clouds. To study Grimsvötn's activity and structure, Fichtner and his colleagues deployed a 12.5-kilometer-long fiber-optic cable that took continuous, real-time measurements of ground vibrations on and around the volcano in May 2021. By tracking how pulses of light travel through the cable, researchers charted ground vibrations at every point along the way.

Upon analysis, the researchers found they had detected nearly 2,000 earthquakes in less than one month—compared with 18 recorded by Iceland's national seismic network, according to study co-author Kristín Jónsdóttir of the Icelandic Meteorological Office. And they also logged a strange, rhythmic vibration from the ice floating atop a lake in the volcano's large central depression, known as the caldera.

An ice sheet, like any solid, inherently vibrates at some natural frequency. If it is subjected to another, bigger jolt that matches that frequency, the vibration will be amplified—like a jackhammer outside causes a kitchen tabletop to rattle. The researchers propose that their mystery hum comes from tiny earthquakes, called volcanic tremors, caused by volcanic and geothermal activity. These tremors are most noticeable near the volcano's caldera, and they can indicate the likelihood of eruption.

"The ice sheet's natural resonance acts as a magnifying glass," Fichtner says—boosting the otherwise unobservable tremors to a detectable level. "To the best of our knowledge, this is a phenomenon that has not been observed before." The work was published in *The Seismic Record*.

This amplifying effect also arises in a very different locale, says Ebru Bozdag, a geophysicist at the Colorado School of Mines, who was not involved in the study. In places such as Los Angeles, she says, "we know that sedimentary basins have the potential to amplify seismic waves, which is what makes them so hazardous. My understanding is that the ice sheet in the volcano might be behaving somewhat similarly."

Tracking geothermal activity, which these natural resonators can reveal, is "critical for knowing what your volcano is doing," says Corentin Caudron, a seismology researcher at the Free University of Brussels, who was not involved in the work. "The study opens great perspective for monitoring glacier-covered volcanoes in Iceland and elsewhere."

—*Rachel Berkowitz*

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GEOLOGY

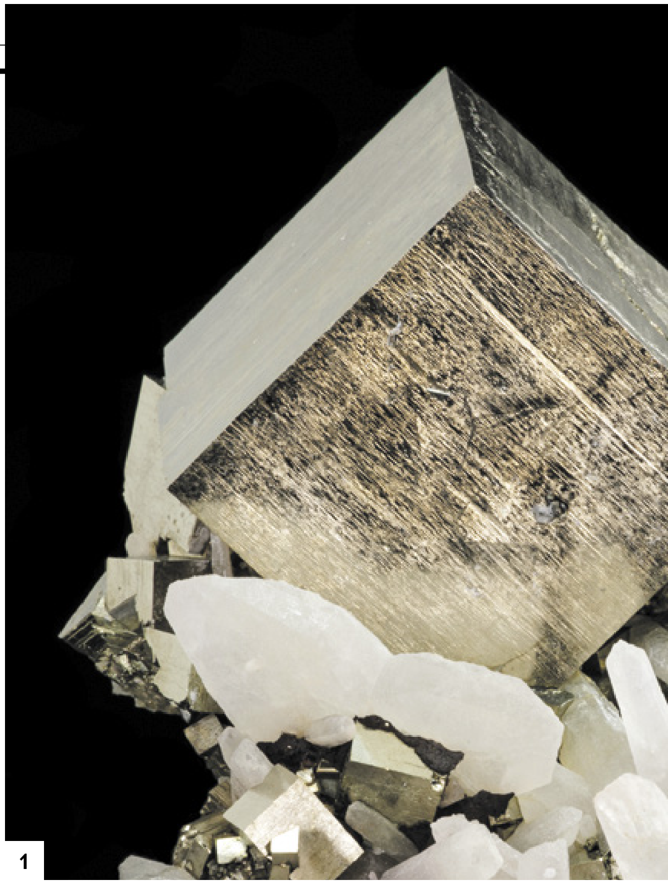
Science in Images

By Fionna M. D. Samuels

Minerals are geologic time capsules of the environments in which they form. With the right approach, their mysteries can be cracked open to reveal key features of the ancient Earth or other planets.

Geologists have traditionally classified minerals by their unique combinations of chemical formula and crystal structure—capturing how, for instance, differences in the way carbon atoms are stacked together lead to slippery graphite layers or rigid diamond. But this 200-year-old formal classification system omits a significant consideration: how the mineral forms.

"What you don't get from this very quantifiable, very definable taxonomy of mineral species is context," says Shaunna Morrison, a mineralogist and planetary scientist at the Carnegie Institution for Science. So with two papers in *American Mineralogist,* Morrison and her colleagues aimed to supplement the old system by classifying all the ways minerals can grow and transform.



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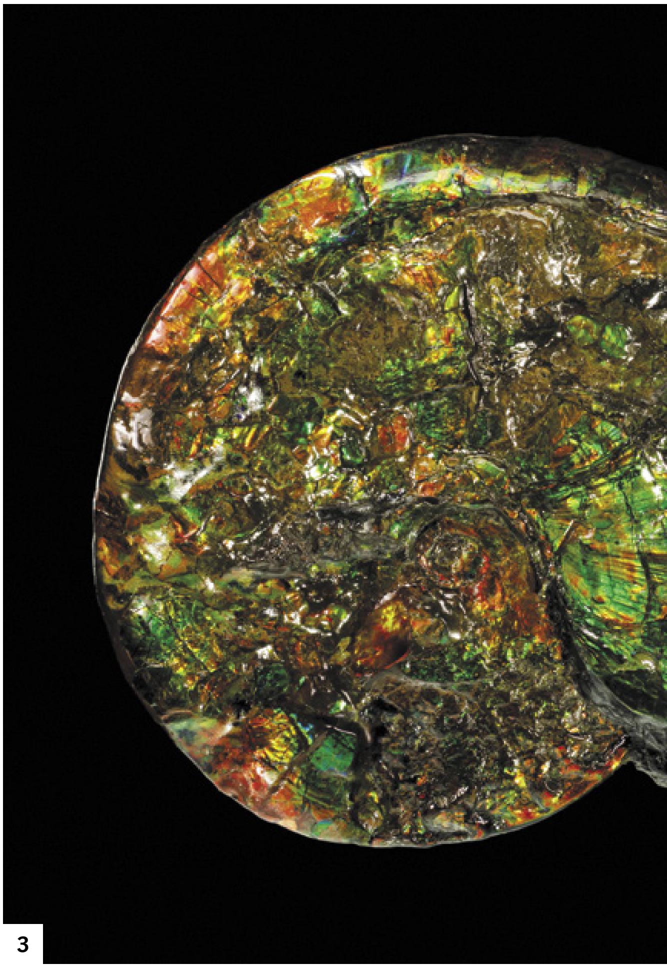
1. The shiny, golden mineral **pyrite** can form in 21 different ways, the researchers report—from crystallizing within volcanic vents to growing with the help of bacteria. Each way has its own chemical fingerprint, formed by trace contaminants and radioactive versions of elements. Morrison is on the Mars Curiosity team, and she hopes to use this kind of detail to identify how that planet's pyrite formed—and if life could have been involved.

2. Eighty percent of the planet's minerals would not exist without water. This **calcite**'s crystallized form reflects changing Ice Age water levels in a cave in southern China. The mineral can form in at least 17 ways.

3. Fossils such as this **opalized ammonite** can develop gradually when a mixture of water and silica permeates deeply buried shells, bones or teeth left behind after other remains rot away. The researchers identified 1,900 minerals that formed as a direct result of biological processes.

4. Life's emergence on Earth directly or indirectly allowed the formation of close to half the planet's mineral types. Some, such as deep green **malachite**, stably formed only after bacteria began exhaling oxygen on early Earth.



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Although the concept of mineral evolution itself is not new, this proposed framework provides "a stimulus to try and get people to think somewhat differently about [mineralogy] and perhaps offer avenues for research that will make the field more robust and interesting," says George Harlow, a geologist who recently redesigned the American Museum of Natural History's mineral hall and was not involved in the new studies.

University of Colorado Boulder mineral physicist Alisha Clark, who was also not involved, says she is going to start incorporating this modified taxonomy in her classroom. She sees it as a way to add some flexibility to the original, rigid mineral classifications: "I think it's exciting to see science evolve and to remember that there are new ways of looking at problems."

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

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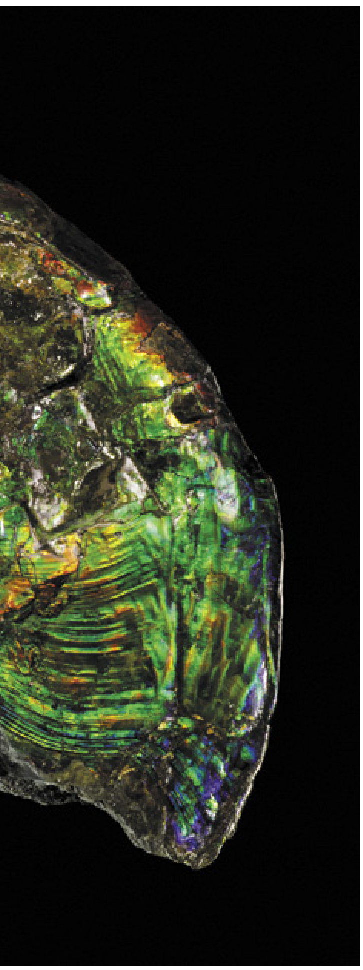

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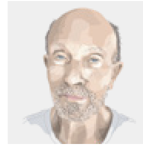
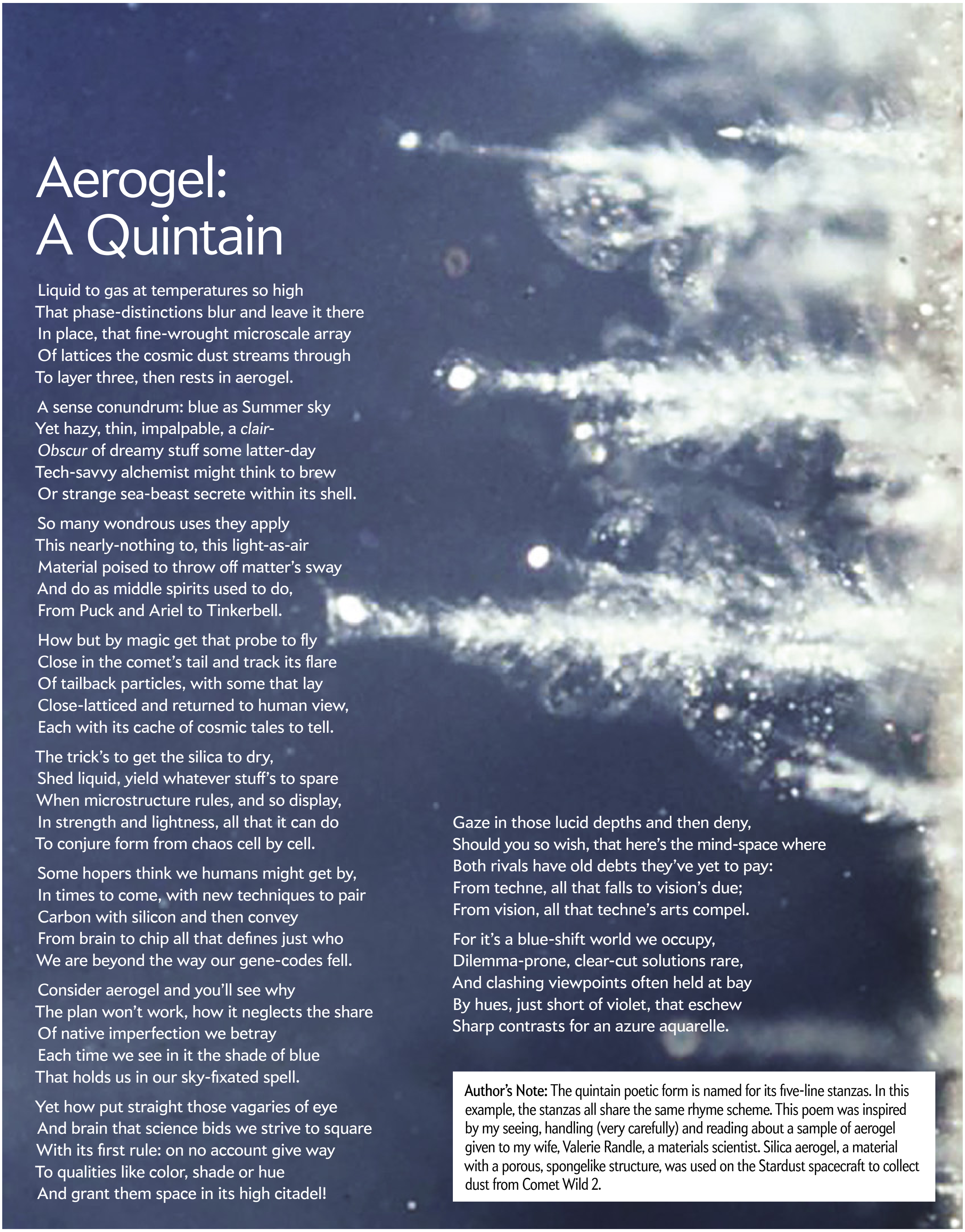
ARKENSTONE/Rob Lavinsky

Christopher Norris is emeritus professor of philosophy at Cardiff University in Wales. He has published eight volumes of poetry and some 40 academic books, four of them treating themes in philosophy of science, such as the defense of scientific realism and conceptual problems in quantum theory.





Aerogel: A Quintain

Liquid to gas at temperatures so high
That phase-distinctions blur and leave it there
In place, that fine-wrought microscale array
Of lattices the cosmic dust streams through
To layer three, then rests in aerogel.

A sense conundrum: blue as Summer sky
Yet hazy, thin, impalpable, a *clair-*
Obscur of dreamy stuff some latter-day
Tech-savvy alchemist might think to brew
Or strange sea-beast secrete within its shell.

So many wondrous uses they apply
This nearly-nothing to, this light-as-air
Material poised to throw off matter's sway
And do as middle spirits used to do,
From Puck and Ariel to Tinkerbell.

How but by magic get that probe to fly
Close in the comet's tail and track its flare
Of tailback particles, with some that lay
Close-latticed and returned to human view,
Each with its cache of cosmic tales to tell.

The trick's to get the silica to dry,
Shed liquid, yield whatever stuff's to spare
When microstructure rules, and so display,
In strength and lightness, all that it can do
To conjure form from chaos cell by cell.

Some hopers think we humans might get by,
In times to come, with new techniques to pair
Carbon with silicon and then convey
From brain to chip all that defines just who
We are beyond the way our gene-codes fell.

Consider aerogel and you'll see why
The plan won't work, how it neglects the share
Of native imperfection we betray
Each time we see in it the shade of blue
That holds us in our sky-fixated spell.

Yet how put straight those vagaries of eye
And brain that science bids we strive to square
With its first rule: on no account give way
To qualities like color, shade or hue
And grant them space in its high citadel!

Gaze in those lucid depths and then deny,
Should you so wish, that here's the mind-space where
Both rivals have old debts they've yet to pay:
From techne, all that falls to vision's due;
From vision, all that techne's arts compel.

For it's a blue-shift world we occupy,
Dilemma-prone, clear-cut solutions rare,
And clashing viewpoints often held at bay
By hues, just short of violet, that eschew
Sharp contrasts for an azure aquarelle.

Author's Note: The quintain poetic form is named for its five-line stanzas. In this example, the stanzas all share the same rhyme scheme. This poem was inspired by my seeing, handling (very carefully) and reading about a sample of aerogel given to my wife, Valerie Randle, a materials scientist. Silica aerogel, a material with a porous, spongelike structure, was used on the Stardust spacecraft to collect dust from Comet Wild 2.

NASA/JPL

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

The Secrets of Thirst

Your body usually knows how much water you need, without arbitrary targets

By Claudia Wallis

Serious question: How much water does the average adult need to drink every day? You've probably heard the usual answer: eight 8-ounce glasses, sometimes stated as 8 × 8. But there's not much science behind this ubiquitous recommendation. A 2002 research review found essentially no reliable studies. Any truly serious answer to the how-much question will begin with some version of "it depends." Are you in a hot location? Are you exerting yourself? Are you in good health? How big are you? Do you eat a lot of salty foods, or do you load up on fruits and vegetables?

We do need water every day, but the average person gets it from many sources: tea or coffee, soft drinks (which often include sugar that you don't need), and food. "We typically get about 20 percent of our fluid requirements from solid foods and about 80 percent from beverages," says Brenda M. Davy, professor of human nutrition at Virginia Tech University. To maintain a healthy balance of water, minerals and salts, health authorities say that adults should drink about a liter (34 ounces) of liquid for every 1,000 kilocalories consumed. That works out to be a little over eight cups for someone who takes in 2,000 daily calories—a possible source of the 8 × 8 notion. But most Americans achieve this level of hydration from a variety of foods and drinks, with about a third coming from plain water, according to a 2013 study of nearly 16,000 U.S. adults.

Natural thirst mechanisms are the reason that most of us do not need to be overly concerned about hydration. The adult body is roughly 60 percent water—closer to 80 percent in the lungs and kidneys—and it carefully controls the concentration of water. We are all familiar with the sensory aspect of this regulation: the dry throat and urgent alert of thirst. But recently neuroscientists have gained other remarkable insights into how thirst is monitored in the body and controlled in the brain.

Researchers have known since the 1950s that a pea-sized structure in the brain's hypothalamus controls thirst. In a series of experiments in which he infused salt into the brains of goats, Swedish physiologist Bengt Andersson showed that a region called the subfornical organ (SFO) monitors the concentration of water and salts in blood and triggers the urge to drink. The SFO plays the same role in people. But Andersson's ideas failed to fully explain how we experience thirst. For instance, when we gulp a drink, we feel almost instantly satisfied, and yet it takes 10 to 15 minutes for a liquid to make it from our mouth, through the digestive tract and into the bloodstream. "Something in the brain is saying that your blood may not have changed conditions yet but that you drank enough water so you can stop feeling thirsty," explains neuroscientist Christopher Zimmerman of Princeton University.

In a series of elegant experiments with mice, Zimmerman and his associates measured the activity of neurons in the SFO. "We saw that their activity changed very fast when the mouse drank water or drank saltwater and when it ate food," he says. Their research showed that signals converged on the SFO from several places. "You get a signal from the blood that tells your current state of hydration, a signal from the mouth that tells you how much fluid you drank, and a signal from the gut that tells you what was consumed—was it water, was it something else?" The SFO neurons, he explains, "add these signals together" and then transmit the urge to drink or stop drinking.

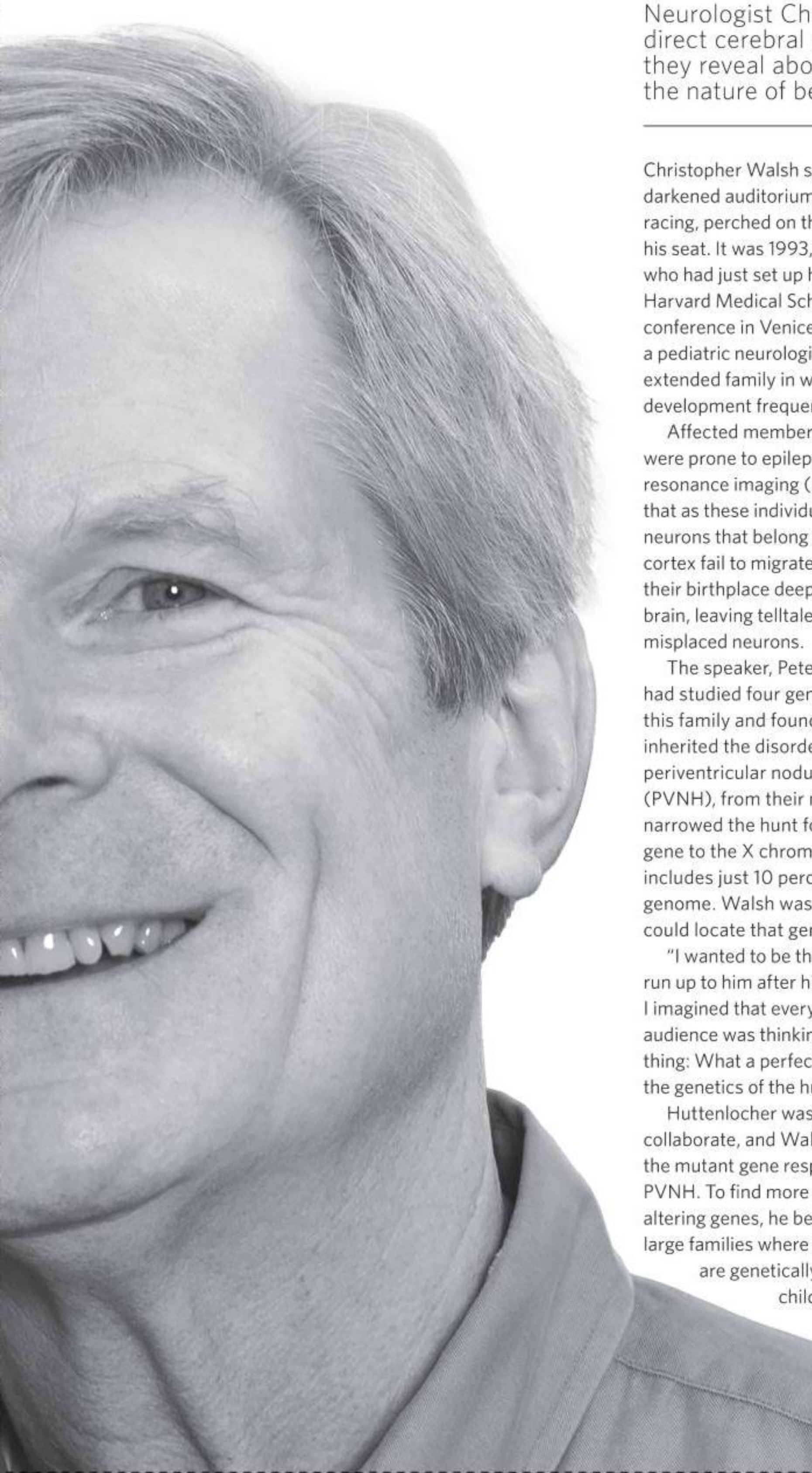
The big takeaway of Zimmerman's work is that for the most part you can trust your thirst system to tell you when you need to drink, as opposed to following some arbitrary advice. But there are exceptions. Because the system's sensitivity may decline with age, older adults may need to set reminders to drink—the 2013 study found that, on average, people older than 70 failed to get adequate hydration. People with certain conditions, including kidney stones and diarrhea, also need extra water. And research by Davy and others indicates that middle-aged and older people who are trying to lose weight or maintain weight loss consume fewer calories if they fill up with 16 ounces of water before meals.

Other parts of the brain—the ones used in planning—should help with hydration on hot days and when exercising. Thirsty or not, Zimmerman says, he drinks water before going for a run: "My thirst neurons don't know I'm about to run 10 miles." SA

Illustration by Fatinha Ramos

REVEALING THE GENES THAT SHAPE THE **HUMAN BRAIN**

Neurologist Christopher Walsh discovered genes that direct cerebral cortex development. We asked him what they reveal about intelligence, psychiatric disorders, and the nature of being human



Christopher Walsh sat in the darkened auditorium, his heart racing, perched on the edge of his seat. It was 1993, and Walsh, who had just set up his lab at Harvard Medical School, was at a conference in Venice, listening to a pediatric neurologist describe an extended family in which early brain development frequently went awry.

Affected members of that family were prone to epilepsy. Magnetic resonance imaging (MRI) revealed that as these individuals develop, neurons that belong in the cerebral cortex fail to migrate there from their birthplace deep inside the brain, leaving telltale blobs of misplaced neurons.

The speaker, Peter Huttenlocher, had studied four generations of this family and found that girls inherited the disorder, called periventricular nodular heterotopia (PVNH), from their mothers. This narrowed the hunt for the faulty gene to the X chromosome—which includes just 10 percent of the genome. Walsh was certain he could locate that gene.

"I wanted to be the first person to run up to him after his talk, because I imagined that everyone else in the audience was thinking the same thing: What a perfect way to study the genetics of the human brain."

Huttenlocher was happy to collaborate, and Walsh identified the mutant gene responsible for PVNH. To find more of these brain-altering genes, he began studying large families where the parents are genetically related and children have a greater chance of inheriting two flawed copies of genes that can jumble brain development.

Ultimately, he identified dozens of genetic mutations that alter brain function and the size and shape of the brain. Many underlie neurological conditions, from epilepsy and schizophrenia to autism spectrum disorders. In one dramatic example, the mutations create a cortical malformation dubbed a "double cortex" in females with this disorder, causing severe seizures and intellectual disability. By studying families with these mutations, Walsh uncovered key mechanisms underlying healthy brain development and revealed how these processes can be derailed by neurological disease.

Walsh, Jean-Louis Mandel, Harry Orr and Huda Zoghbi shared the 2022 Kavli Prize in Neuroscience for their discovery of genes that underlie serious brain disorders.

Here, Walsh contemplates why psychiatric conditions are still so hard to comprehend, why structural anomalies don't necessarily derail mental function, whether genetics can give us a handle on consciousness, and how autism research could help reveal what makes us human.

How do mutations lead to schizophrenia and other psychiatric conditions?

As a neurologist, I think about the brain in terms of having localized functions. You've got an area for language and an area for vision. I was hoping that we might discover mutations that affect a particular part of the brain, but the genes disrupted in psychiatric disease tend to be genes that are expressed in all neurons. Yet schizophrenia is associated with specific, reproducible symptoms: Individuals hear voices, they become paranoid, they lose their ability to run thoughts together in a logical fashion. This favors the existence of some sort of circuit—but the circuit seems to be all over the place. So this is still an unanswered question.

How can anatomically diverse brains produce brilliant minds?

Individuals with PVNH have blobs of neurons that are clearly in the wrong place. Yet some of these people are CEOs or medical students or computer programmers, and some have IQs of 140. Surprisingly, it looks like they are using those abnormally placed neurons to think. The neurons appear to be wired up to the regular cortex—sometimes in weird ways. It's just a completely different way of putting the brain together.

I sometimes think of the cerebral cortex as a part of the brain that evolved to dodge genetics. We have all these parts that are evolutionarily and functionally conserved, like the brain stem, the cerebellum, and the hypothalamus. Yet the cortex seems to be fairly unspecified in its design. It's like how you buy a big hard drive, thinking you'll figure out later what you'll do with it. The cortex is like the expansion slot on your computer.

What makes our brains uniquely human?

When it comes to understanding what makes us human, it seems like our best shot is to do it through the genome. By comparing our genome to the genomes of chimps and Neanderthals, we can look for "human-accelerated regions," which are conserved in our nearest neighbors but are a little different in humans. This suggests that they have an essential function but that in humans, that function might have changed a bit. There are thousands of these human-accelerated regions in our genome. We prioritize those that are mutated in neurological diseases. That's how nature identifies the parts of the genome that are critical: disruptions in those regions correspond with disease. Mutations in some human-accelerated regions are more common in children with autism spectrum disorder. So the study of medical genetics may give us the best chance we have of understanding human evolution—and autism may help us understand what makes us human.

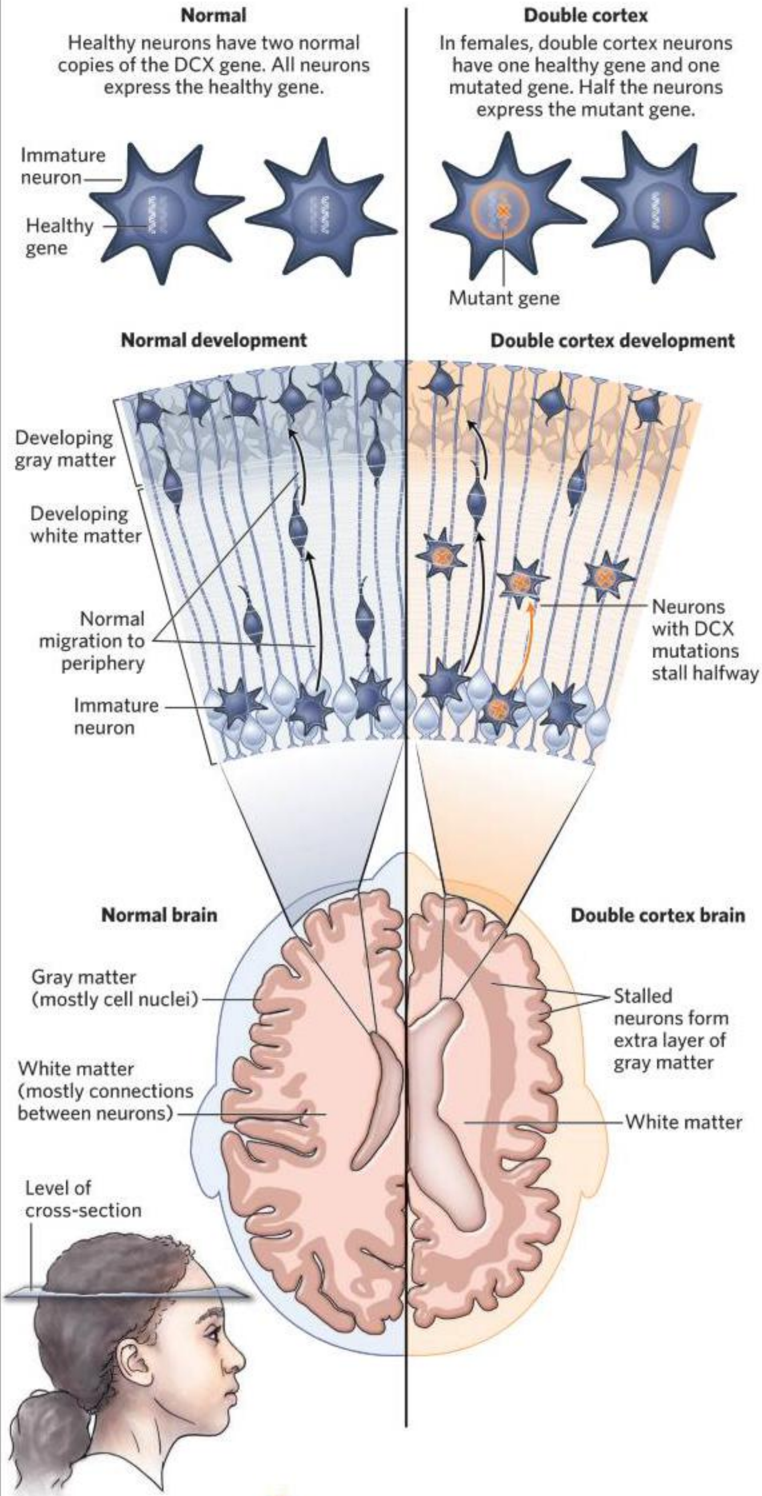
What are the roots of consciousness?

The whole idea that consciousness and behavior are mediated by a bunch of cells and chemicals—how is that even possible? In theory, if we knew that the mind or consciousness is unique to humans, then doing enough genome sequencing might allow us to identify segments that vary between humans and nonhumans. And that could give us a way to get at the question. The problem is, we don't even understand the mental processes of our fellow humans, much less how other animals experience the world. Our dog seems to have a sense of "personhood." Where in the brain does this sense of identity reside? I don't know, and I'm not sure that we have the experimental tools we need to tackle that problem. It remains a fascinating question.

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

HOW MUTATIONS DISRUPT BRAIN DEVELOPMENT

Immature neurons normally climb outwards from the center of the embryonic brain toward the developing cortex. Mutations that disrupt migration, such as double cortex, cause serious neurological disorders.



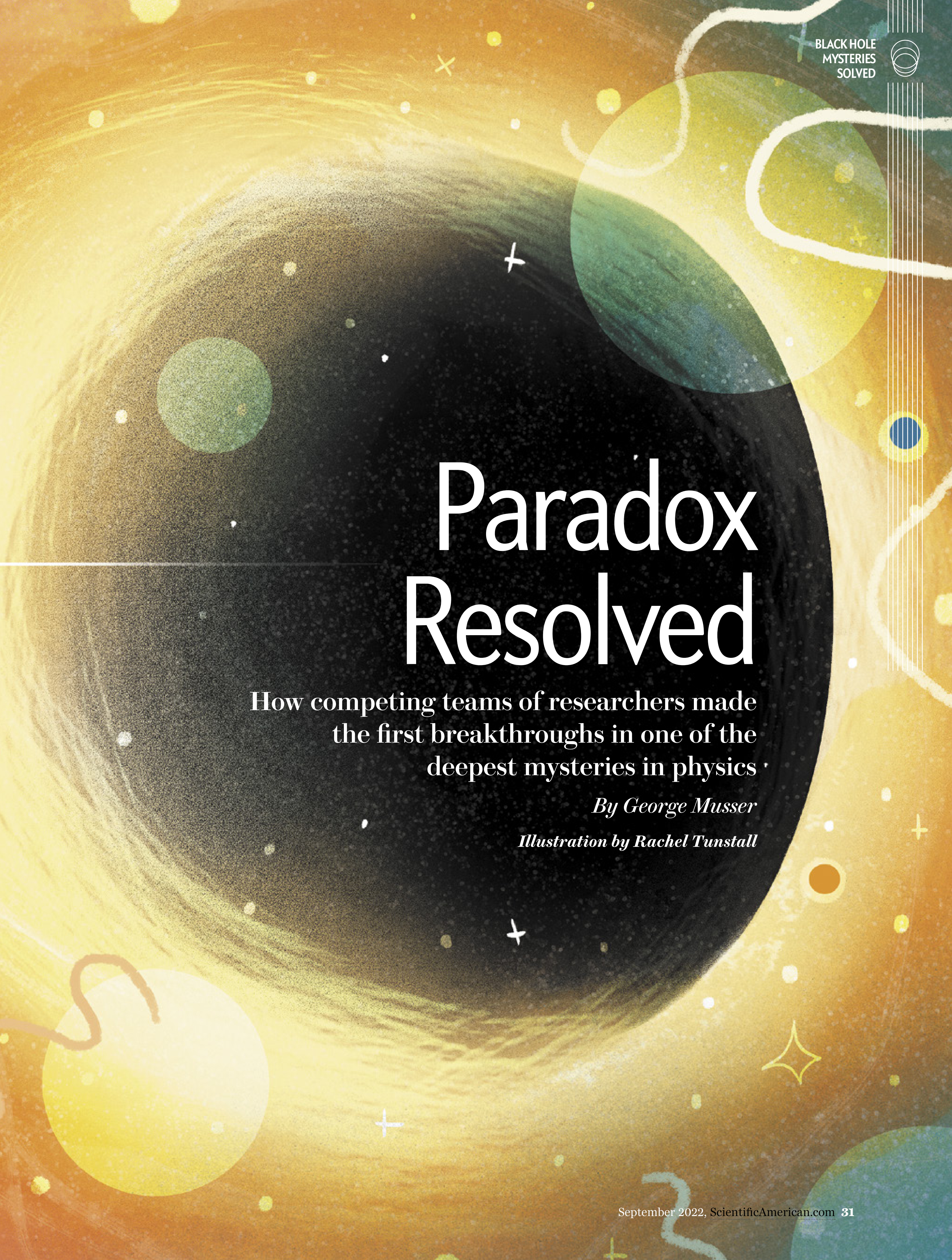
THE KAVLI PRIZE

BLACK HOLE MYSTERIES SOLVED

Illustration by Olena Shmahalo

TO MANY PEOPLE, BLACK HOLES EVOKE A MYSTERIOUS DARKNESS THREATENING TO SWALLOW YOU UP. To scientists, they have sometimes seemed like the mystery that might swallow physics. They awkwardly bridge the theories of quantum mechanics and general relativity, exposing deep weaknesses in our understanding of nature. But recent theoretical and observational advances have helped illuminate these shadowy objects, with profound implications for more than just black holes themselves.

On page 30, George Musser describes how physicists have made breakthroughs toward resolving a decades-old quandary called the black hole information paradox. One of the physicists involved in this work, Ahmed Almheiri, explains the mind-bending solution on page 34. Another physicist, Edgar Shaghoulian, discusses on page 42 how these insights may even help scientists better understand the cosmos as a whole. And on page 48, Seth Fletcher writes about the Event Horizon Telescope, which has captured the first image of the black hole at the center of the Milky Way. Black holes are starting to look a little less dark and enigmatic. *—Clara Moskowitz, Senior Editor*



Paradox Resolved

How competing teams of researchers made the first breakthroughs in one of the deepest mysteries in physics

By George Musser

Illustration by Rachel Tunstall

George Musser is a contributing editor at *Scientific American* and author of *Spooky Action at a Distance* (Farrar, Straus and Giroux, 2015) and *The Complete Idiot's Guide to String Theory* (Alpha, 2008). Follow him on Twitter @gmusser

A FEW YEARS AGO A TEAM OF CHEMISTS UNBOILED AN EGG. BOILING CAUSES PROTEIN molecules in the egg to twist around one another, and a centrifuge can disentangle them to restore the original. The technique is of dubious utility in a kitchen, but it neatly demonstrates the reversibility of physics. Anything in the physical world can run both ways—it's one of the deepest features of the laws of physics, reflecting elemental symmetries of space, time and causality. If you send all the parts of a system into reverse, what was done will be undone. The information required to wind back the clock is always preserved. Of course, undoing a process may be easy in simple systems but is less so in complex ones, which is why the egg unboiler was so nifty.

But there's a troubling exception: black holes. If a massive enough star collapses under its own weight, its gravity intensifies without limit and locks matter in its grip. Jump into one, and there's no going back. Merge two together, and you can't split them apart. A black hole presents an almost completely featureless façade to the universe. Looking at it, you can't tell what fell in. The black hole does not seem to preserve information. This irreversibility, first appreciated by physicist David Finkelstein in 1958, was the earliest inkling of the black hole information paradox—"paradox" because how could reversible laws have irreversible effects? The paradox signaled a deeper disease in physicists' understanding of the world. Scientists have many reasons to seek a grand unified theory of nature, but the information paradox is their most specific motivation, and it has guided their way when they have little else to go on.

At last, more than 60 years after this puzzle began to appear, physicists are seeing hope for a solution. In the year leading up to the pandemic and through the months of lockdown, a coalition of theorists took huge strides to understand the paradox—the most progress in decades, some say. They bolstered the idea that black holes, despite appearances, are reversible, and they dissolved the official paradox. Physical theory is no longer at odds with itself. The work is contentious, though, and by its proponents' own admission, it is at best a starting point for a full explanation of black holes.

Until recently, most of the "progress" physicists have made on this paradox over the decades has consisted of realizing the problem is even harder than they'd thought. Finkelstein's original work left loopholes. For one, it was based on Einstein's general theory of relativity, which physicists knew was not the full story, because it left out quantum effects. In the 1970s Stephen Hawking—in the work that made him a household name—took a first crack at including those effects. His calculations predicted that black holes slowly release energy. But this emission carries no information about whatever had fallen in, so it doesn't help wind back the clock. If anything, the outgoing trickle of particles worsens the predicament. The black hole eventually empties itself of energy and evaporates away like a puddle on a summer's day. All the matter it imprisoned is not freed but wiped out of existence. Hawking's analysis elevated a general unease into a full-fledged crisis for physics.

In 1993 Hawking's former graduate student Don N. Page, now at the University of Alberta, dug the hole even deeper. He showed that if a black hole is to disgorge its information, it can't wait until its dying moments but has to begin roughly halfway through its lifetime. That's significant because a middle-aged black hole will have shrunk only modestly from its original size and should still be governed by the ordinary laws of physics. So physicists can't just pin the entire problem on unknown exotic physics; it signals an inconsistency within even the best-established of theories. In 2009 Samir D. Mathur of the Ohio State University further showed that slight tweaks to Hawking's calculations won't do. Something big is missing.

The key element in Page's and Mathur's analyses was quantum entanglement, a special kind of correlation that particles can have even when no force or other influence links them. Entanglement is mysterious in its own right, but physicists can set that aside and ask what it means for black holes. Most particles that fall into one are entangled with particles that remain outside, and these linkages must be maintained if the black hole is to preserve information. Yet the linkages can't simply be transferred to the outgoing particles that Hawking postulated, at least not without causing other troubles, according to an influential study by Ahmed Almheiri of the Institute for Advanced Study in Princeton, N.J., and his colleagues in 2013.

So black holes may be reversible, but theorists' confusion goes only one way. On the bright side, studying the paradox has spun off ideas about gravity, spacetime and the unification of physics. For one thing, black holes imply that space has a limited capacity to hold material—you can pack in stuff only so tightly before it implodes to form a black hole. Oddly, the storage capacity of space scales up with a region's area rather than with its volume. Space looks three-dimensional but acts as if it were two-dimensional. It has an illusory quality that we are usually oblivious to but that becomes evident in a black hole.

That realization is the origin of what became known as the holographic principle, one of the most fascinating—and baffling—ideas in modern theoretical science. It says that at least one of the spatial dimensions we experience is not fundamental to nature but instead emerges from quantum dynamics. The best-developed version of the holographic principle is the so-called AdS/CFT (anti–de Sitter space/conformal field theory) duality. It conceives of the universe as a gigantic snow globe. In one version, a three-dimensional space called the bulk (AdS) is encased within a two-dimensional boundary (CFT). Bulk and boundary are mathematically equivalent ("dual"), although theorists often consider the boundary to be more fundamental and the bulk to emerge from it. Whatever happens in the bulk has a parallel in the shadow world of the boundary. If a planet orbits a star in the bulk, the shadows of the planet and star do a little dance on the boundary.

Scientists have refined this duality over the years. Today not only can physicists equate a 3-D space to a 2-D space, they can match specific parts of the 3-D space to specific parts of the 2-D one. They can also associate particular physical quantities on both sides. The most advanced version of this correspondence, developed by Netta Engelhardt of the Massachusetts Institute of Technology and Aron Wall of the University of Cambridge in 2014, relates the area of surfaces to the amount of quantum entanglement. These very different quantities are secretly the same, and this equivalence gives theorists a glimpse of the underlying unity of nature.

With all these ingredients in place, theorists were recently able to make a new assault on the black hole information paradox. In 2019 Almheiri, Engelhardt and their colleagues, and independently Geoff Penington of the University of California, Berkeley (who was using broadly similar methods), were able to show how information could escape from black holes in the way Page had prescribed. (Read more about this breakthrough in Almheiri's article on page 34.) In so doing the researchers confirmed that black holes are reversible after all. Later the same year these and other authors, again working in two parallel teams, double-checked that the outgoing radiation bears the information that the black hole lets out. This time their calculations did not directly rely on the AdS/CFT duality. Instead they adopted essentially the same mathematical techniques as Hawking's. If, as Page argued, the paradox lay in well-established theories, its resolution should not hinge on anything so fancy as AdS/CFT.

The teams confirmed that it doesn't. A black hole builds up such a gargantuan amount of entanglement that the geometry of spacetime undergoes a dramatic transition. Spacetime inside and around the black hole takes on convoluted shapes, including wormholes that resemble the spacetime portals of science fiction. These wormholes connect the interior of the black hole to the outside world, although how they enable information to escape is still unclear. Bizarre though this geometric transition may sound, it fits perfectly well into existing physics. Whatever else you may say about black holes, they are no longer paradoxical—they don't represent an internal inconsistency within current theories.

These calculations were daunting even by the standards of modern physics. Skeptics were impressed, although that didn't stop them from poking holes in the argument. By the time the debate was in full swing, however, the pandemic hit, and science went into lockdown. In-person meetings resumed only at the end of 2021. Some physicists say that science by Zoom just isn't the same and that proponents and skeptics have yet to really engage with one another. "Maybe this is partly a function of the pandemic, that there is more splintering of the field," says Suvrat Raju of the Tata Institute of Fundamental Research in Bangalore.

In one especially sharp critique, Raju and his colleagues complained that the two teams' setup is highly contrived. To a degree, the same can be said of most theoretical models, but this one makes idealizations that are not at all innocent, these authors say. For instance, it supposes that gravity not only weakens with distance but eventually shuts off altogether. That assumption fundamentally changes the nature of this force, so that the calculations, though technically correct, say little about gravity or black holes in the real world.

Mathur and others also argued that the new work implies a nonlocal effect—one that does not propagate through space but jumps from one place to another—to extract information from the black hole. That in itself is not surprising. Physicists broadly agree that black holes require nonlocal effects to make sense. But the specific type of nonlocality in the new analyses strikes some skeptics as implausible.

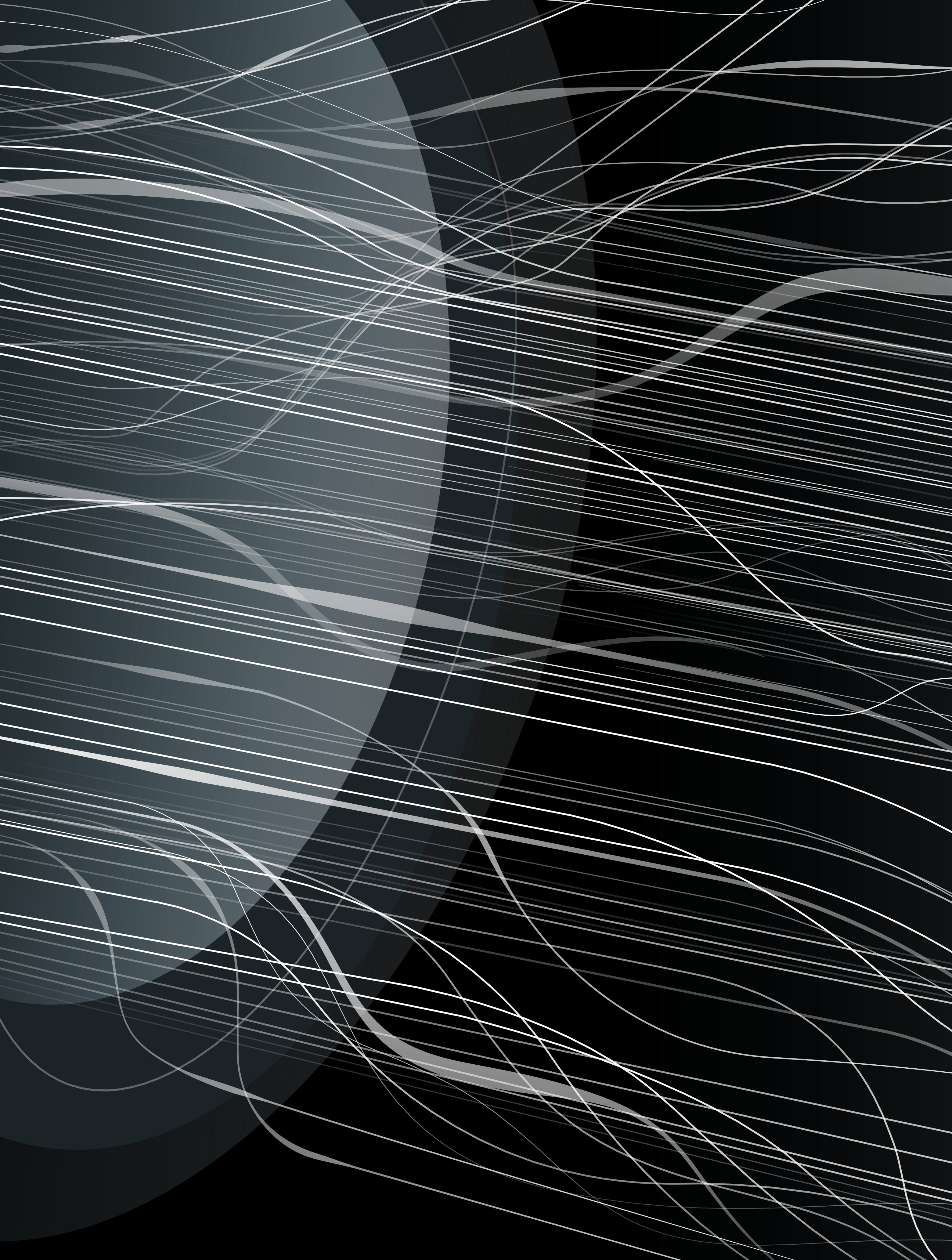
Both Raju and Mathur advocate alternative solutions to the information paradox. Raju suggested that information doesn't have to get out of a black hole, because it is already out. Gravity has a long tail—the force acts over an unlimited range—that prevents information from ever being bottled up in the first place, he says. The gravitational, electromagnetic and other quantum fields outside the black hole retain an imprint of whatever falls in. "This region is rich in information," Raju says. Mathur, for his part, argues that true black holes never actually form. As a star starts to collapse, it awakens the exotic physics of string theory, according to which all particles are vibration patterns in a more primitive type of matter. Stringy physics arrests the collapse, leaving a highly compact star, also known as a fuzzball. This little star does not wall itself off gravitationally, and information rides out on its light.

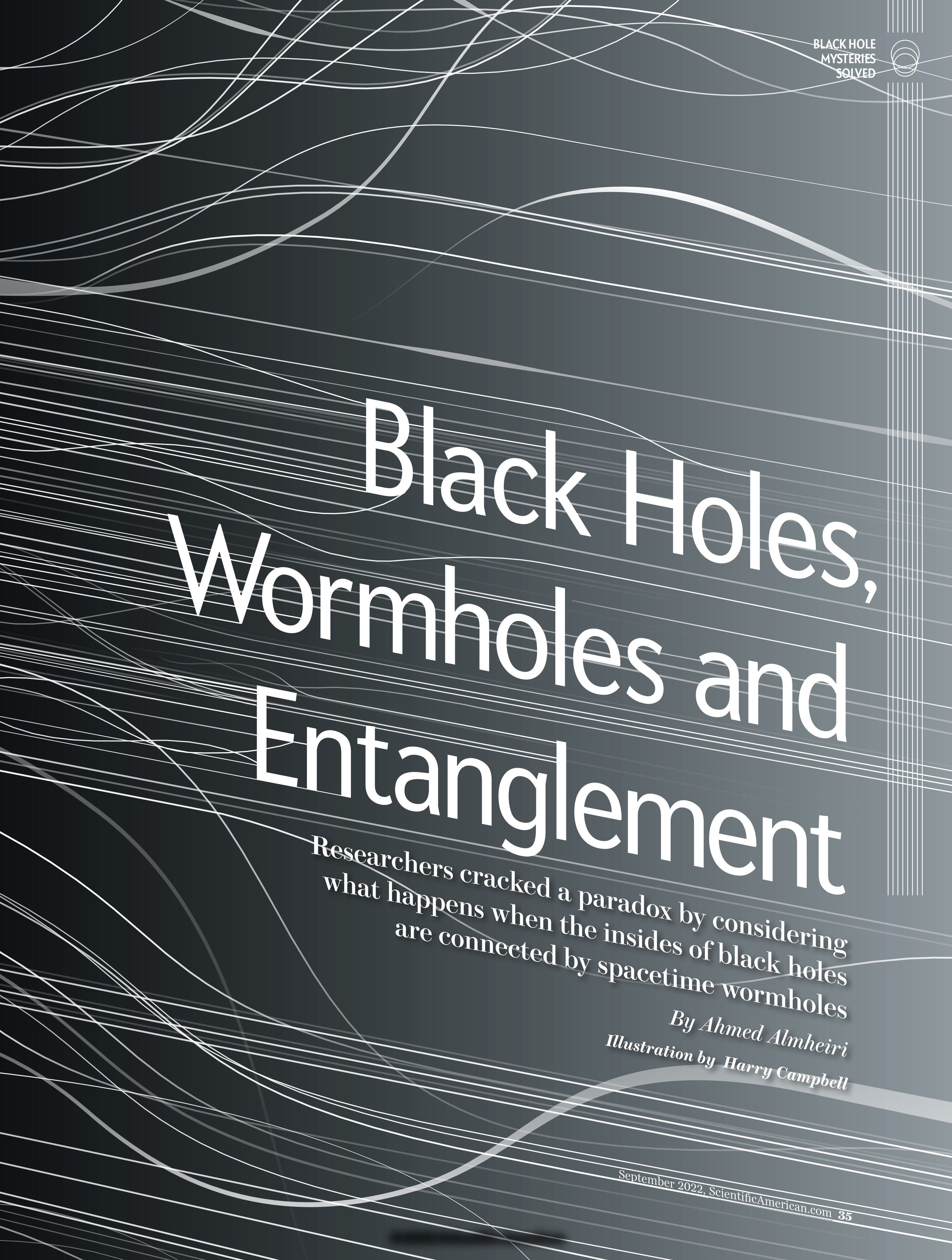
These ideas and their variants have critics, too. Indeed, Mathur and Raju disagree with each other's approaches. So the nature of black holes is still up for grabs. And continuing the historical trend, theorists are doing better at finding new puzzles than at solving old ones. In recent years Leonard Susskind of Stanford has noted yet another paradox of black holes. Space inside them is so stretchy that their interior volume should grow forever. Such expansion, however, would violate the principle that any closed system will reach equilibrium. Some heretofore unsuspected physics must eventually intervene to stabilize the interior.

Susskind and others also find that black holes are frenetically chaotic systems, swirling and seething underneath their featureless façades. This aspect of black holes, at least, can be studied in computer simulations and laboratory experiments. Creating a real black hole is beyond them, but experimentalists are looking at the same chaotic dynamics in ions, condensates and other material systems. They run the system, then unwind it; bringing it back to its exact starting point requires exquisite precision, demonstrating how black holes can look irreversible even if, in principle, they are rewindable.

Meanwhile theorists think that what goes for black holes may go for the universe as a whole. Because our universe is expanding at an accelerating rate, it has a one-way surface much like that of a black hole's event horizon, and physicists hope that insights about black holes will offer up secrets of the cosmos as well. (Read more about this idea in Edgar Shaghoulian's article on page 42.)

Truth be told, physicists are happy black holes are proving so tough to figure out. If the problem is this hard, the solution has got to be profound. SA





Black Holes, Wormholes and Entanglement

Researchers cracked a paradox by considering what happens when the insides of black holes are connected by spacetime wormholes

By Ahmed Almheiri

Illustration by Harry Campbell

Ahmed Almheiri is a theoretical physicist at New York University in Abu Dhabi, United Arab Emirates, where he studies the connections between quantum information and quantum gravity.

THEORETICAL PHYSICS HAS BEEN IN CRISIS MODE EVER SINCE 1974, WHEN STEPHEN HAWKING argued that black holes destroy information. Hawking showed that a black hole can evaporate, gradually transforming itself and anything it consumes into a featureless cloud of radiation. During the process, information about what fell into the black hole is apparently lost, violating a sacred principle of physics.

This has been an open problem for more than 45 years, but the pieces started falling into place in 2019 through research that I was involved in. The resolution is based on a new understanding of spacetime and how it can be rewired through quantum entanglement, which leads to the idea that part of the inside of a black hole, the so-called island, is secretly on the outside.

To understand how we arrived at these new ideas, we must begin with the inescapable nature of black holes.

A ONE-WAY STREET

NOTHING SEEMS MORE HOPELESS than trying to get out of a black hole—in fact, this impossibility is what defines it. Black holes are formed when enough matter is confined within a small enough region that spacetime collapses in on itself in a violent feedback loop of squeezing and stretching that fuels more squeezing and stretching. These tidal forces run to infinity in finite time, marking the abrupt end of an entire region of spacetime at the so-called black hole singularity—the place where time stops and space ceases to make sense.

There is a fine line within the collapsing region that divides the area where escape is possible from the point of no return. This line is called the event horizon. It is the outermost point from which light barely avoids falling into the singularity. Short of traveling faster than light—a physical impossibility—nothing can escape from behind the event horizon; it is irretrievably lodged inside the black hole.

The one-way nature of this boundary is not immediately problematic. In fact, it is a robust prediction of the general theory of relativity. The danger starts when this theory interacts with the wild world of quantum mechanics.

SOMETHING OUT OF NOTHING

QUANTUM THEORY REDEEMS BLACK HOLES from being the greedy monsters they are made out to be. For every calorie of energy they consume, they eventually give it back in the form of Hawking radiation—energy squeezed out of the vacuum near the event horizon.

The idea of getting something out of nothing may sound absurd, but absurdity is not the worst allegation made against quantum mechanics. The emptiness of the vacuum in quantum theory belies a sea of particles—photons, electrons, gravitons, and more—that conspire to make empty space feel empty. These particles come in carefully arranged pairs, acting hand in hand as the glue that holds spacetime together.

Particle pairs that straddle the event horizon of a black hole, however, become forever separated from one another. The newly divorced particles peel away from the horizon in opposite directions, with one member crashing into the singularity and the other escaping the black hole's gravitational pull in the form of Hawking radiation. This process is draining for the black hole, causing it to get lighter and smaller as it emits energy in the form of the outgoing particles. Because of the law that energy must be conserved, the particles trapped inside must then carry negative energy to account for the decrease in the total energy of the black hole.

From the outside, the black hole appears to be burning away (although it happens so slowly, you can't see it happening in real life). When you burn a book, the words on its pages imprint themselves on the pattern of the emanating light and the remaining ashes. This information is thus preserved, at least in principle. If an evaporating black hole were a normal system like the burning book, then the information about what falls into it would be encoded into the emerging Hawking radiation. Unfortunately, this is complicated by the quantum-mechanical relation among the particles across the horizon.

EINSTEIN'S ENEMY

THE ISSUE BEGINS WITH THE END of the union of the two particles straddling the event horizon. Despite being separated, they maintain a quantum union that transcends space and time—they are connected by entanglement. Rejected as an absurdity by the physicists who predicted it, quantum entanglement is perhaps one of the weirdest aspects of our universe and arguably one of its most essential. The concept was first concocted by Albert Einstein, Boris Podolsky and Nathan Rosen as a rebuttal against what was then the nascent theory of quantum mechanics. They cited entanglement as a reason the theory must be incomplete—"spooky" is how Einstein famously described the phenomenon.

A simple example of entanglement is to consider two coins in a superposition—the quantum phenomenon of being in multiple states until a measurement is made—of both coins being either heads or tails. The coins aren't facing heads and tails at the same time—that's physically impossible—but the superposition signifies that the chance of observing the pair of coins in either orientation, both heads or both tails, is a probability of one half. There is no chance of ever finding the coins in opposite orientations. Hence, the two coins are entangled; the measurement result of one predicts the result of the other with complete certainty. Any coin by itself is completely random, devoid of information, but the randomness of the pair is perfectly correlated.

The scientists were troubled by how the two coins appeared to influence one another without having to come into physical contact. The coins could be in separate galaxies while still maintaining the same amount of entanglement between them. Einstein was unnerved by the apparent "spooky action at a distance" linking the results of the two separate random measurements.

The irony is that Einstein himself is in a superposition of being both wrong and right. He was right to recognize the importance of entanglement in distinguishing quantum mechanics from classical physics. What he got wrong can be summed up with the truism "correlation does not imply causation." Although the fates of the particles are inextricably correlated, the measurement outcome of one does not *cause* the outcome of the other. It turns out that quantum mechanics simply allows for a new, higher degree of correlation than we are used to.

THE IDEA OF GETTING SOMETHING OUT OF NOTHING MAY SOUND ABSURD, BUT ABSURDITY IS NOT THE WORST ALLEGATION MADE AGAINST QUANTUM MECHANICS.

INFORMATION LOST

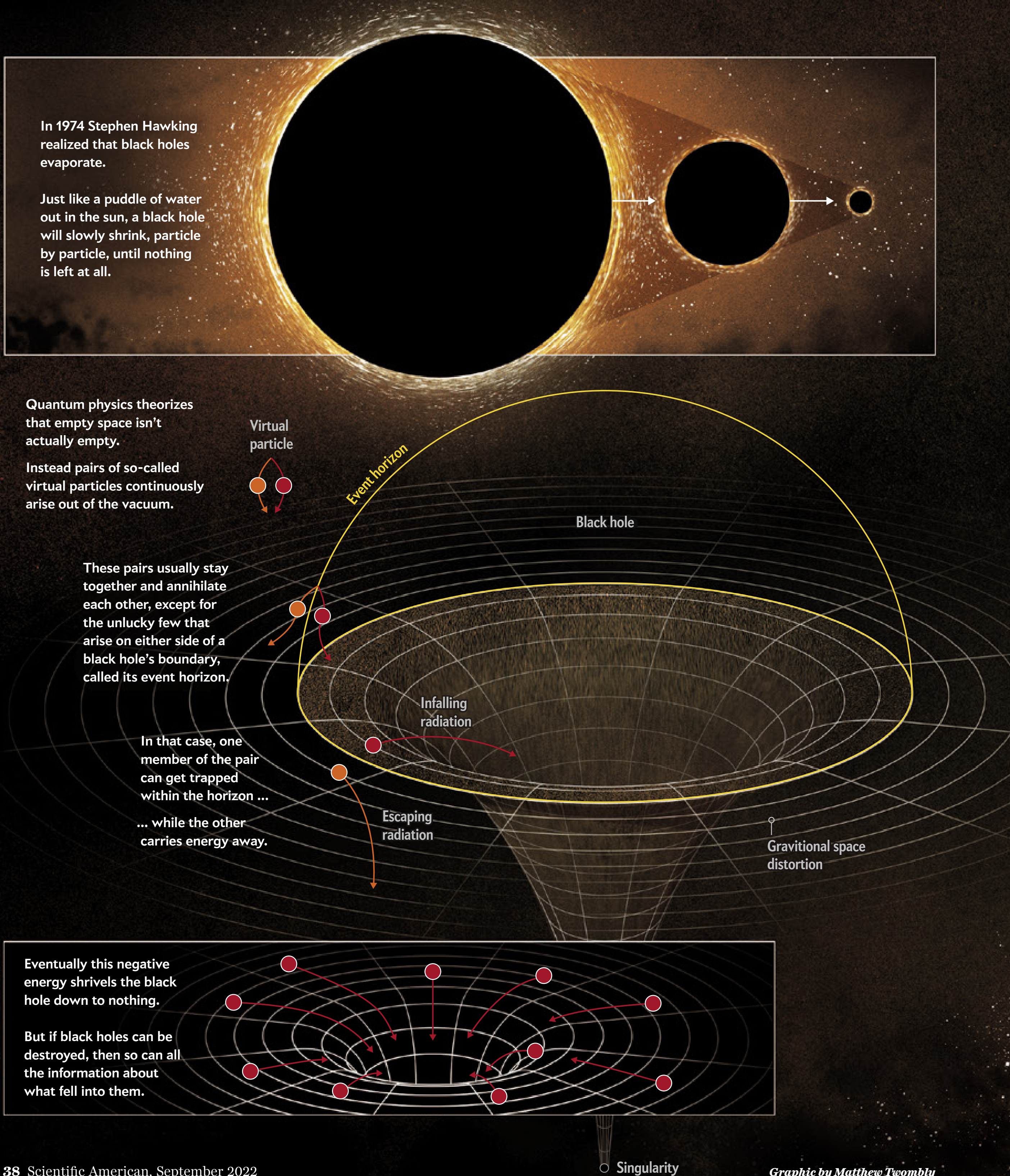
BECAUSE HAWKING RADIATION is composed of one half of a collection of entangled pairs, it emerges from the black hole in a completely random state—if they were coins, they would be observed to be heads or tails with equal probability. Hence, we cannot infer anything useful about the contents of the black hole from the random measurements of the radiation. This means that an evaporating black hole is basically a glorified information shredder, except unlike the mechanical kind, it does a thorough job.

We can measure the lack of information—or the randomness—in the Hawking radiation by thinking about the amount of entanglement between the radiation and the black hole. This is because one member of an entangled pair is always random, and the outside members are all that remains by the end of the evaporation. The calculation of randomness goes by many names, including entanglement entropy, and it grows with every emerging Hawking particle, plateauing at a large value once the black hole has completely disappeared.

This pattern differs from what happens when information is preserved, as in the example of a burning book. In such a case, the entropy may rise initially, but it has to peak and fall down to zero by the end of

The Black Hole Information Paradox

For almost half a century physicists have agonized over the question of what happens to the stuff that falls into a black hole. If, as theory predicts, black holes destroy information about everything that has ever fallen in, then our theories of nature are in deep, foundational trouble. In recent years, though, scientists have made a breakthrough that might finally solve the puzzle.



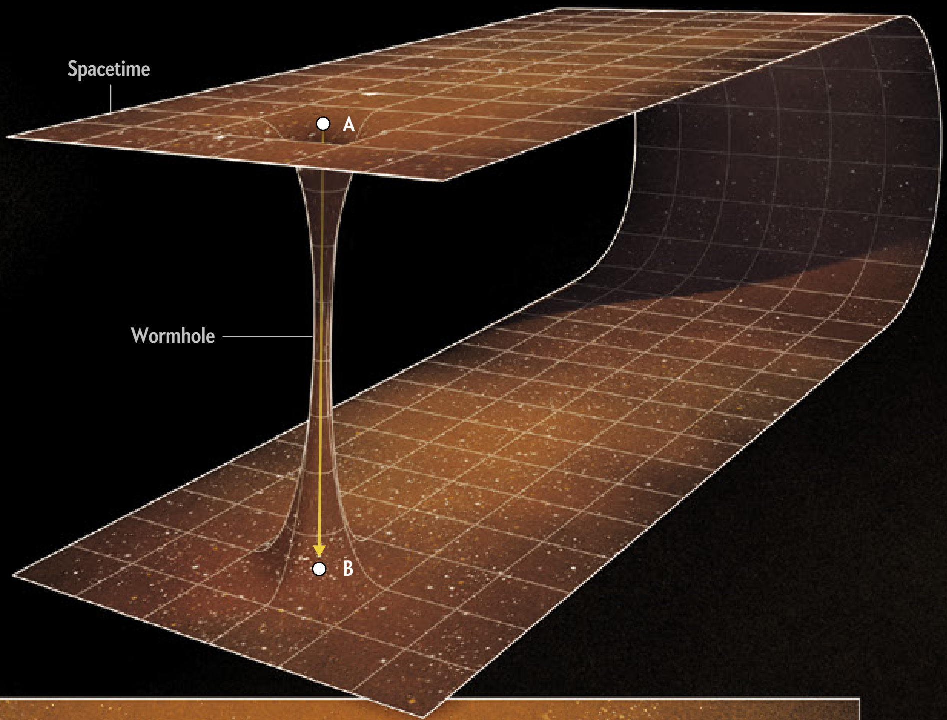
Graphic by Matthew Twombly

That seems to break a fundamental law of physics, which says that information can never be destroyed.

This is the paradox.

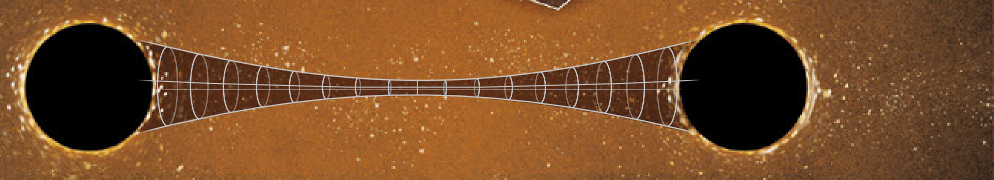
In the past few years a unique solution has revealed itself: wormholes.

Wormholes are theoretical bridges in spacetime that connect two distant spots through a shortcut.



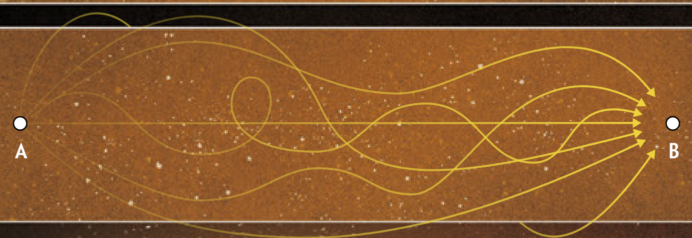
The inside of a black hole could be connected to the inside of another black hole via a wormhole.

Though rare, it's theoretically possible.



And in quantum physics, everything that can happen does happen.

A particle doesn't simply travel along one particular path from point A to point B.



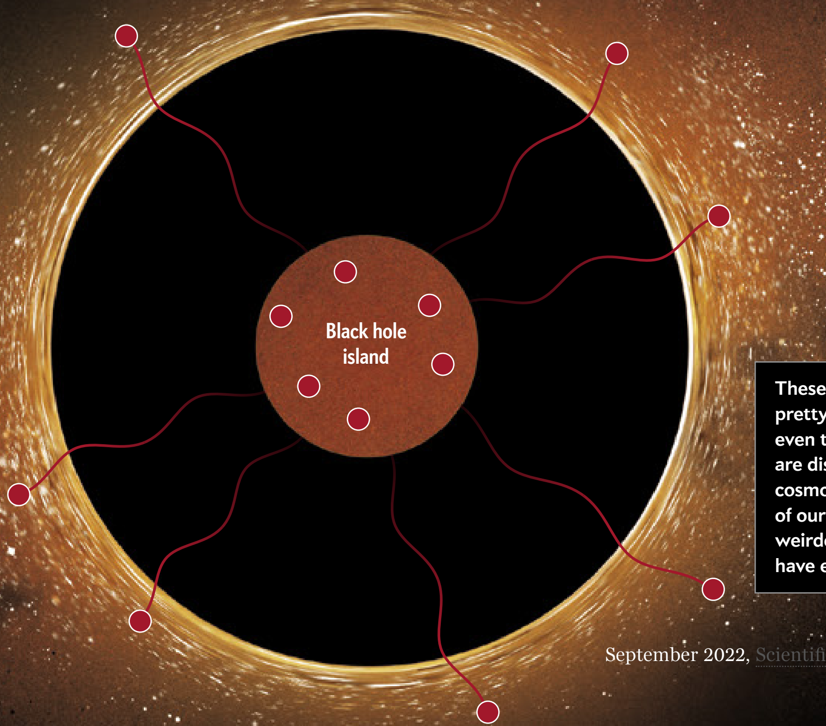
It takes all of them simultaneously.

If wormholes are at the center of black holes, information pulled within may not be destroyed.

Instead the interiors of black holes seem to contain special areas deep inside called islands.

These islands are both inside and outside the black holes, as if they are part of the escaping radiation that is depleting the black holes over time.

And as they escape, the information within them escapes, too.



These new ideas are pretty confounding, even to physicists, who are discovering that the nature of the cosmos and the nature of our reality are even weirder than we could have ever imagined.

the process. The intuition behind this rule is clear when you think about a standard deck of cards: suppose you are dealt cards from a 52-card deck, one by one, facing down. The entropy of the cards in your possession is simply a measure of your ignorance of what's on the other side of the cards—specifically, the number of possibilities of what they could be. If you have been dealt just one card, the entropy is 52 because there are 52 possibilities. But as you are dealt more, the entropy rises, peaking at 500 trillion for 26 cards, which could be any of 500 trillion different combinations. After this, though, the possible mixes of cards, and thus the entropy, goes back down, reaching 52 again when you have 51 cards. Once you have all the cards, you are certain of exactly what you have—the entire deck—and the entropy is zero. This rising and falling pattern of entropy, known as the Page curve, applies to all normal quantum-mechanical systems. The time at which the entropy peaks and starts to decrease is the Page time.

EVENTUALLY MY COLLEAGUES AND I REALIZED THAT BOTH THE INFORMATION PARADOX AND THE NEWER FIREWALL PARADOX AROSE BECAUSE OUR ATTEMPTS TO MELD QUANTUM MECHANICS AND BLACK HOLE PHYSICS WERE TOO TIMID.

The destruction of information inside black holes spells disaster for physics because the laws of quantum mechanics stipulate that information cannot be obliterated. This is the famous information paradox—the fact that a sprinkling of quantum mechanics onto the description of black holes leads to a seemingly insurmountable inconsistency. Physicists knew we needed a more complete understanding of quantum-gravitational physics to generate the Page curve for the Hawking radiation. Unsurprisingly, this task proved difficult.

AN EVENTFUL HORIZON

PART OF THE CHALLENGE was that no minor tweaking of the evaporation process was sufficient to generate the Page curve and send the entropy back down to zero. What we needed was a drastic reimagining of the structure of a black hole.

In a paper I published in 2013 with Donald Marolf, Joseph Polchinski and Jamie Sully (known collectively as AMPS), we tried out several ways to modify the picture of evaporating black holes using a series of *Gedanken* experiments—the German term for the kind of thought experiments Einstein popularized. Through our trials we concluded that to save the sanctity of information, one of two things had to give: either physics must be nonlocal—allowing for information to instantaneously disappear from the interior and appear outside the event horizon—or a new process must kick in at the Page time. To preclude the increase of entropy, this process would have to break the entanglement between the particle pairs across the event horizon. The former option—making physics nonlocal—was too radical, so we decided to go with the latter.

This modification helps to preserve information, but it poses another paradox. Recall that the entanglement across the horizon was a result of having empty space there—the way the vacuum is maintained by a sea of entangled pairs of particles. The entanglement is key; breaking it comes at the cost of creating a wall of extremely high-energy particles, which our group named the firewall. Having such a firewall at the horizon would forbid anything from entering the black hole. Instead infalling matter would be vaporized on contact. The black hole at the Page time would suddenly lose its interior, and spacetime would come to an end, not at the singularity deep inside the black hole but right there at the event horizon. This conclusion is known as the firewall paradox, a catch-22 that meant any solution to the information paradox must come at the cost of destroying what we know about black holes. If there was ever a quagmire, this would be it.

FLUCTUATING WORMHOLES

EVENTUALLY MY COLLEAGUES and I realized that both the information paradox and the newer firewall paradox arose because our attempts to meld quantum mechanics and black hole physics were too timid. It wasn't enough to apply quantum mechanics to only the matter present in black holes—we had to devise a quantum treatment of the black hole spacetime as well. Although quantum effects on spacetime are usually very small, they could be enhanced by the large entanglement produced by the evaporation. Such an effect may be subtle, but its implications would be huge.

To consider the quantum nature of spacetime, we relied on a technique designed by Richard Feynman called the path integral of quantum mechanics. The idea is based on the weird truth that, according to quantum theory, particles don't simply travel along a single path from point A to point B—they travel along *all* the different paths connecting the two points. The path integral is a way of describing a particle's travels in terms of a quantum superposition of all possible routes. Similarly, a quantum spacetime can be in a superposition of different complicated shapes evolving in different ways. For instance, if we start and end with two regular black holes, the quantum spacetime within them has a nonzero probability of creating a short-lived wormhole that temporarily bridges their interiors.

Usually the probability of this happening is vanishingly slim. When we carry out the path integral in the presence of the Hawking radiation of multiple black holes, however, the large entanglement between the Hawking radiation and the black hole interiors amplifies the likelihood of such wormholes. This realization came to me through work I did in 2019 with Thomas Hartman, Juan Maldacena, Edgar Shaghoulian and Amirhossein Tajdini, and it was also the result of an independent collaboration between Geoffrey Penington, Stephen Shenker, Douglas Stanford and Zhenbin Yang.

ISLANDS BEYOND THE HORIZON

WHY DOES IT MATTER if some black holes are connected by wormholes? It turns out that they modify the answer of how much entanglement entropy there is between the black hole and its Hawking radiation. The key is to measure this entanglement entropy in the presence of multiple copies of the system. This is known as the replica trick.

The relevant physical effect of these temporary wormholes is to swap out the interiors among the different black holes. This happens literally—what was in one black hole gets shoved into one of the other copies far away, and it assumes a new spacetime interior from a different black hole. The swapped region of the black hole interior is called the island, and it encompasses almost the entire interior up to the event horizon.

The swapping is exactly what the doctor ordered! Focusing on one of the black holes and its Hawking radiation, swapping out the island takes with it all the partner particles that are entangled with the outgoing Hawking radiation, and hence, technically, there is no entanglement between the black hole and its radiation.

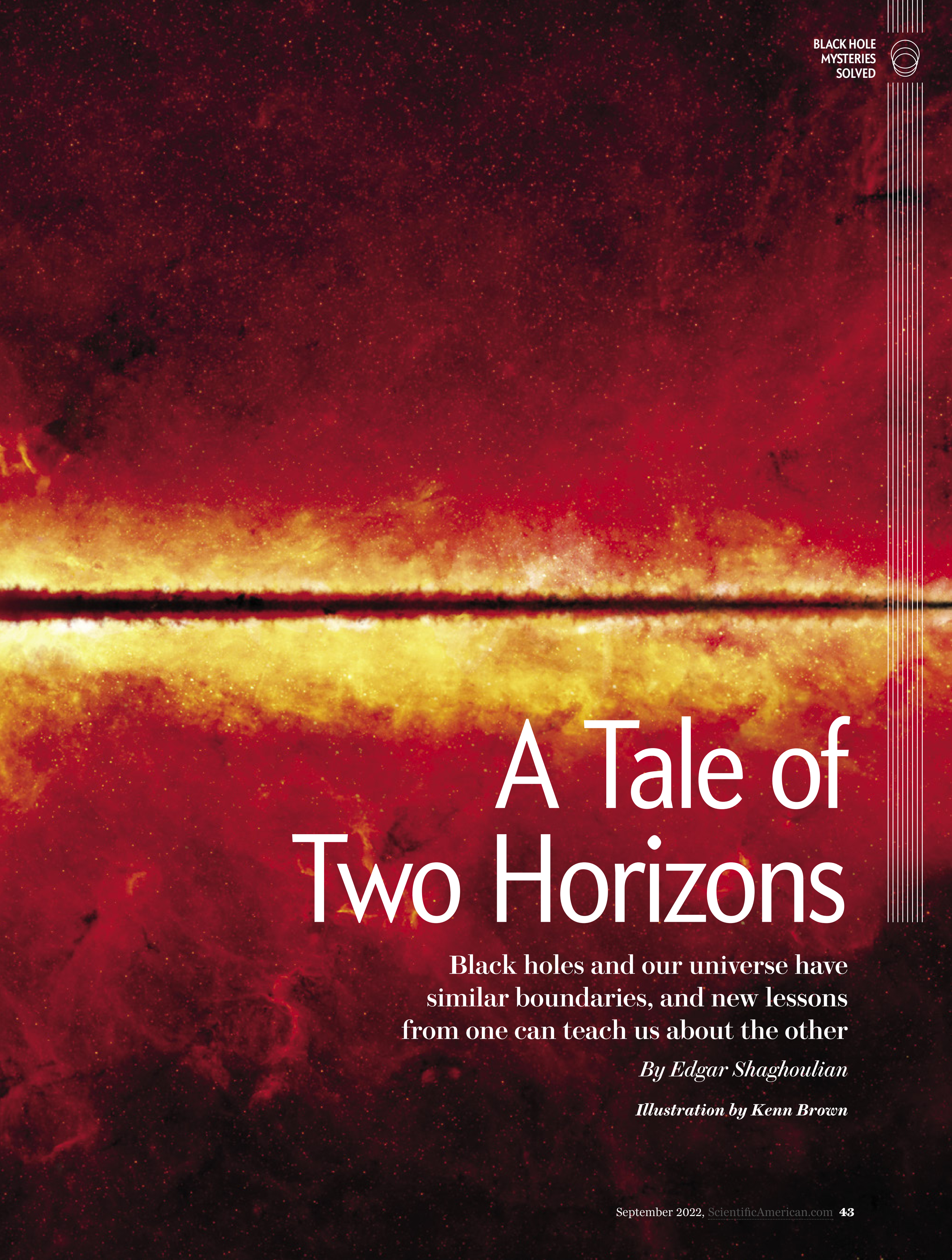
Including this potential effect of wormholes produces a new formula for the entanglement entropy of the radiation when applied to a single copy of the system. Instead of Hawking's original calculation, which simply counts the number of Hawking particles outside of a black hole, the new formula curiously treats the island as if it were outside and a part of the exterior Hawking radiation. Therefore, the entanglement between the island and the exterior should not be counted toward the entropy. Instead the entropy that it predicts comes almost entirely from the probability of the swap actually occurring, which is equal to the area of the boundary of the island—roughly the area of the event horizon—divided by Newton's gravitational constant. As the black hole shrinks, this contribution to the entropy decreases. This is the island formula for the entanglement entropy of the Hawking radiation.

The final step in computing the entropy is to take the minimum between the island formula and Hawking's original calculation. This gives us the Page curve that we've been after. Initially we calculate the entanglement entropy of the radiation with Hawking's original formula because the answer starts off smaller than the area of the event horizon of the black hole. But as the black hole evaporates, the area shrinks, and the new formula takes the baton as the true representative of the radiation's entanglement entropy.

What is remarkable about this result is that it solves two paradoxes with one formula. It appears to address the firewall paradox by supporting the option of nonlocality that my AMPS group originally dismissed. Instead of breaking the entanglement at the horizon, we are instructed to treat the inside—the island—as part of the outside. The island itself becomes nonlocally mapped to the outside. And the formula solves the information paradox by revealing how black holes produce the Page curve and preserve information.

Let's take a step back and think about how we got here. The origins of the information paradox can be traced back to the incompatibility between the sequestering of information by the event horizon and the quantum-mechanical requirement of information flow outside the black hole. Naive resolutions of this tension lead to drastic modifications of the structure of black holes; however, subtle yet dramatic effects from fluctuating wormholes change everything. What emerges is a self-consistent picture that lets a black hole retain its regular structure as predicted by general relativity, albeit with the presence of an implicit though powerful nonlocality. This nonlocality is screaming that we should consider a portion of the black hole's interior—the island—as part of the exterior, as a single unit with the outside radiation. Thus, information can escape a black hole not by surmounting the insurmountable event horizon but by simply falling deeper into the island.

Despite the excitement of this breakthrough, we have only begun to explore the implications of spacetime wormholes and the island formula. Curiously, while they ensure that the island is mapped onto the radiation, they do not generate a definite prediction for specific measurements of the Hawking radiation. What they do teach us, however, is that wormholes are the missing ingredient in Hawking's original estimation of the randomness in the radiation and that gravity is in fact smart enough to comply with quantum mechanics. Through these wormholes, gravity harnesses the power of entanglement to achieve nonlocality, which is just as unnerving to us as the entanglement that originally spooked Einstein. We must admit that, at some level, Einstein was right after all.



A Tale of Two Horizons

Black holes and our universe have similar boundaries, and new lessons from one can teach us about the other

By Edgar Shaghoulian

Illustration by Kenn Brown

Edgar Shaghoulian is a theoretical physicist at the Center for Particle Cosmology at the University of Pennsylvania. His work focuses on black holes and quantum cosmology.

WHERE DID THE UNIVERSE COME FROM? WHERE IS IT HEADED? ANSWERING THESE QUESTIONS requires that we understand physics on two vastly different scales: the cosmological, referring to the realm of galaxy superclusters and the cosmos as a whole, and the quantum—the counterintuitive world of atoms and nuclei.

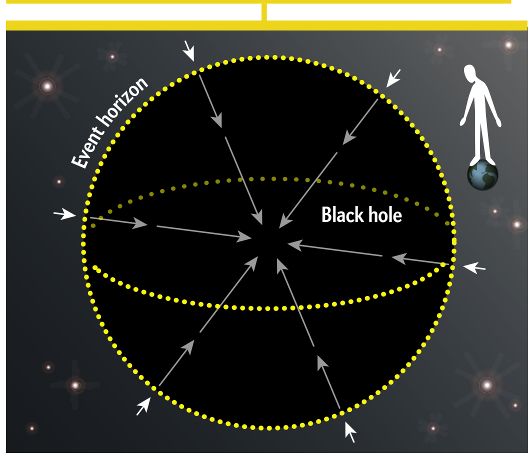
For much of what we would like to know about the universe, classical cosmology is enough. This field is governed by gravity as dictated by Einstein's general theory of relativity, which doesn't concern itself with atoms and nuclei. But there are special moments in the lifetime of our universe—such as its infancy, when the whole cosmos was the size of an atom—for which this disregard for small-scale physics fails us. To understand these eras, we need a quantum theory of gravity that can describe both the electron circling an atom and Earth moving around the sun. The goal of quantum cosmology is to devise and apply a quantum theory of gravity to the entire universe.

Quantum cosmology is not for the faint of heart. It is the Wild West of theoretical physics, with little more than a handful of observational facts and clues to guide us. Its scope and difficulty have called out to young and ambitious physicists like mythological sirens, only to leave them foundering. But there is a palpable feeling that this time is different and that recent breakthroughs from black hole physics—which also required understanding a regime where quantum mechanics and gravity are equally important—could help us extract some answers in quantum cosmology. The fresh optimism was clear at a recent virtual physics conference I attended, which had a dedicated discussion session about the crossover between the two fields. I expected this event to be sparsely attended, but instead many of the luminaries in physics were there, bursting with ideas and ready to get to work.

EVENT HORIZONS

THE FIRST INDICATION that there is any relation between black holes and our universe as a whole is that both manifest "event horizons"—points of no return beyond which two people seemingly fall out of contact forever. A black hole attracts so strongly that at some point even light—the fastest thing in the universe—cannot escape its pull.

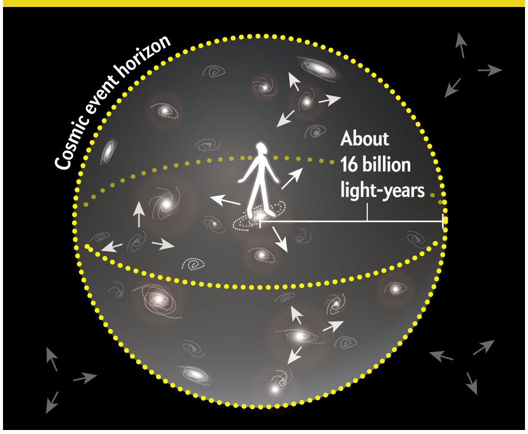
The boundary where light becomes trapped is thus a spherical event horizon around the center of the black hole.



Our universe, too, has an event horizon—a fact confirmed by the stunning and unexpected discovery in 1998 that not only is space expanding, but its expansion is *accelerating*. Whatever is causing this speedup has been called dark energy. The acceleration traps light just as black holes do: as the cosmos expands, regions of space repel one another so strongly that at some point not even light can overcome the separation. This inside-out situation leads to a spherical cosmological event horizon that surrounds us, leaving everything beyond a certain distance in darkness. There is a crucial difference between cosmological and black hole event horizons, however. In a black hole, spacetime is collapsing toward a single point—the singularity. In the universe at large, all of space is uniformly growing, like the surface of a balloon that is being inflated. This means that creatures in faraway galaxies will have their own distinct spherical event horizons, which surround

Graphics by Jen Christiansen

them instead of us. Our current cosmological event horizon is about 16 billion light-years away. As long



as this acceleration continues, any light emitted today that is beyond that distance will never reach us. (Cosmologists also speak of a particle horizon, which confusingly is often called a cosmological horizon as well. This refers to the distance beyond which light emitted in the early universe has not yet had time to reach us here on Earth. In our tale, we will be concerned only with the cosmological event horizon, which we will often just call the cosmological horizon. These are unique to universes that accelerate, like ours.)

The similarities between black holes and our universe don't end there. In 1974 Stephen Hawking showed that black holes are not completely black: because of quantum mechanics, they have a temperature and therefore emit matter and radiation, just as all thermal bodies do. This emission, called Hawking radiation, is what causes black holes to eventually evaporate away. It turns out that cosmological horizons also have a temperature and emit matter and radiation because of a very similar effect. But because cosmological horizons surround us and the radiation falls inward, they reabsorb their own emissions and therefore do not evaporate away like black holes.

Hawking's revelation posed a serious problem: if black holes can disappear, so can the information contained within them—which is against the rules of quantum mechanics. This is known as the black hole information paradox, and it is a deep puzzle complicating the quest to combine quantum mechanics and gravity. But in 2019 scientists made dramatic progress. Through a confluence of conceptual and technical advances, physicists argued that the information inside a black hole can actually be accessed from the Hawking radiation that leaves the black hole. (For more on how scientists figured this out, see the article on page 34 by my colleague Ahmed Almheiri.)

This discovery has reinvigorated those of us studying quantum cosmology. Because of the mathematical similarities between black holes and cosmological horizons, many of us have long believed that we couldn't understand the latter without understanding the former. Figuring out black holes became a warm-up problem—one of the hardest of all time. We haven't fully solved our warm-up problem yet, but now we have a new set of technical tools that provide beautiful insight into the interplay of gravity and quantum mechanics in the presence of black hole event horizons.

ENTROPY AND THE HOLOGRAPHIC PRINCIPLE

PART OF THE RECENT PROGRESS on the black hole information paradox grew out of an idea called the holographic principle, put forward in the 1990s by Gerard 't Hooft of Utrecht University in the Netherlands and Leonard Susskind of Stanford University. The holographic principle states that a theory of quantum gravity that can describe black holes should be formulated not in the ordinary three spatial dimensions that all other physical theories use but instead in two dimensions of space, like a flat piece of paper. The primary argument for this approach is quite simple: a black hole has an entropy—a measure of how much stuff you can stick inside it—that is proportional to the two-dimensional area of its event horizon.

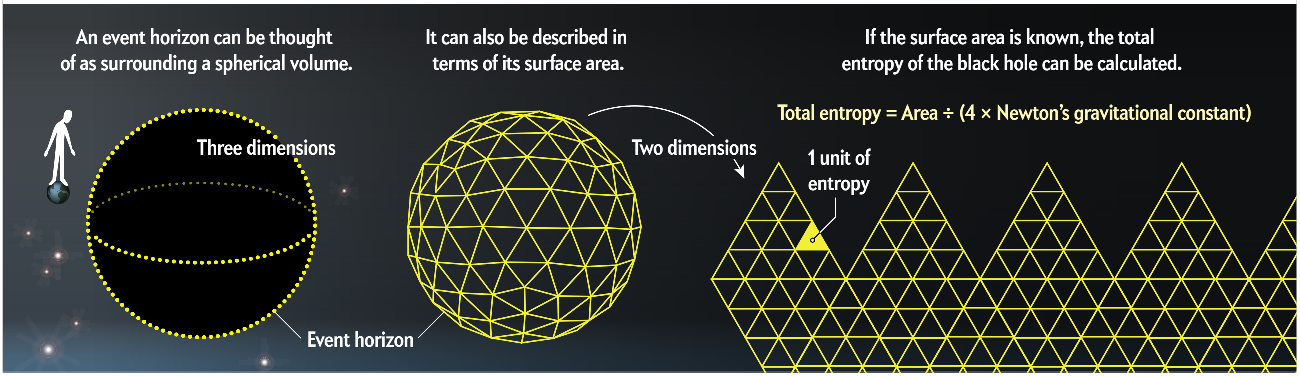
Contrast this with the entropy of a more traditional system—say, a gas in a box. In this case, the entropy is proportional to the three-dimensional volume of the box, not the area. This is natural: you can stick something at every point in space inside the box, so if the volume grows, the entropy grows. But because of the curvature of space within black holes, you can actually increase the volume without affecting the area of the horizon, and this will not affect the entropy! Even though it naively seems you have three dimensions of space to stick stuff in, the black hole entropy formula tells you that you have only two dimensions of space, an area's worth. So the holographic principle says that because of the presence of black holes, quantum gravity should be formulated as a more prosaic nongravitational quantum system in fewer dimensions. At least then the entropies will match.

The idea that space might not be truly three-dimensional is rather compelling, philosophically. At least one dimension of it might be an emergent phenomenon that arises from its deeper nature rather than being explicitly hardwired into the fundamental laws. Physicists who study space now understand that it can emerge from a large collection of simple constituents, similar to other emergent phenomena such as consciousness, which seems to arise from basic neurons and other biological systems.

One of the most exciting aspects of the progress in the black hole information paradox is that it points toward a more general understanding of the holographic principle, which previously had been made precise only in situations very different from our real universe. In the calculations from 2019, however, the way the information inside of the black hole is encoded in the Hawking radiation is mathematically analogous to how a gravitational system is encoded in

The Holographic Principle

An important concept for understanding black holes is the holographic principle. The principle states that a quantum theory of gravity that can describe black holes should be formulated in two dimensions—like the surface of their spherical event horizons—not three, like the volume inside. The reason has to do with the black hole's entropy, which is a measure of the amount of stuff you can stick inside of it. This entropy depends on the area of the black hole, not the volume.



a lower-dimensional nongravitational system according to the holographic principle. And these techniques can be used in situations more like our universe, giving a potential avenue for understanding the holographic principle in the real world. A remarkable fact about cosmological horizons is that they also have an entropy, given by the exact same formula as the one we use for black holes. The physical interpretation of this entropy is much less clear, and many of us hope that applying the new techniques to our universe will shed light on this mystery. If the entropy is measuring how much stuff you can stick beyond the horizon, as with black holes, then we will have a sharp bound on how much stuff there can be in our universe.

OUTSIDE OBSERVERS

THE RECENT PROGRESS on the black hole information paradox suggests that if we collect all the radiation from a black hole as it evaporates, we can access the information that fell inside the black hole. One of the most important conceptual questions in cosmology is whether the same is possible with cosmological event horizons. We think they radiate like black holes, so can we access what is beyond our cosmological event horizon by collecting its radiation? Or is there some other way to reach across the horizon? If not, then most of our vast, rich universe will eventually be lost forever. This is a grim image of our future—we will be left in the dark.

Almost all attempts to get a handle on this question have required physicists to artificially extricate themselves from the accelerating universe and imagine viewing it from the outside. This is a crucial simplifying assumption, and it more closely mimics a black hole, where we can cleanly separate the observer from the system simply by placing the observer far away. But there seems to be no escaping our cosmological horizon; it surrounds us, and it moves if we move, making this problem much more difficult. Yet if we want to apply our new tools from the study of black holes to the problems of cosmology, we must find a way to look at the cosmic horizon from the outside.

There are different ways to construct an outsider view. One of the simplest is to consider a hypothetical auxiliary universe that is quantum-mechanically entangled with our own and investigate whether an observer in the auxiliary universe can access the information in our cosmos, which is beyond the observer's horizon. In work I did with Thomas Hartman and Yikun Jiang, both at Cornell University, we constructed examples of auxiliary universes and other scenarios and showed that the observer can access information beyond the cosmological horizon in the same way that we can access information beyond the black hole horizon. (A complementary paper by Yiming Chen of Princeton University, Victor Gorbenko of EPFL in Switzerland and Juan Maldacena of the Institute for Advanced Study [IAS] in Princeton, N.J., showed similar results.)

But these analyses all have one serious deficiency: when we investigated "our" universe, we used a model universe that is *contracting* instead of expanding. Such universes are much simpler to describe in the context of quantum cosmology. We don't completely understand why, but it's related to the fact that we can think of the interior of a black hole as a contracting universe where everything is getting squished together. In this way, our newfound understanding of black holes could easily help us study this type of universe

Even in these simplified situations, we are puzzling our way through some confusing issues. One problem is that it's easy to construct multiple simultaneous outsider views so that each outsider can access the information in the contracting universe. But this means multiple people can reach the same piece of information and manipulate it independently. Quantum mechanics, however, is exacting: not only does it forbid information from being destroyed, it also forbids information from being replicated. This idea is known as the no-cloning theorem, and the multiple outsiders seem to violate it. In a black hole, this isn't a problem, because although there can still be many outsiders, it turns out that no two of them can independently access the same piece of information in the interior. This limit is related to the fact that there is only one black hole and therefore just one event horizon. But in an expanding spacetime, different observers have different horizons. Recent work that Adam Levine of the Massachusetts Institute of Technology and I did together, however, suggests that the same technical tools from the black hole context work to avoid this inconsistency as well.

TOWARD A TRUER THEORY

ALTHOUGH THERE HAS BEEN EXCITING PROGRESS, so far we have not been able to directly apply what we learned about black hole horizons to the cosmological horizon in our universe because of the differences between these two types of horizons.

The ultimate goal? No outsider view, no contracting universe, no work-arounds: we want a complete quantum theory of our expanding universe, described from our vantage point within the belly of the beast. Many physicists believe our best bet is to come up with a holographic description, meaning one using fewer than the usual three dimensions of space. There are two ways we can do this. The first is to use tools from string theory, which treats the elementary particles of nature as vibrating strings. When we configure this theory in exactly the right way, we can provide a holographic description of certain black hole horizons. We hope to do the same for the cosmological horizon. Many physicists have put a lot of work into this approach, but it has not yet yielded a complete model for an expanding universe like ours.

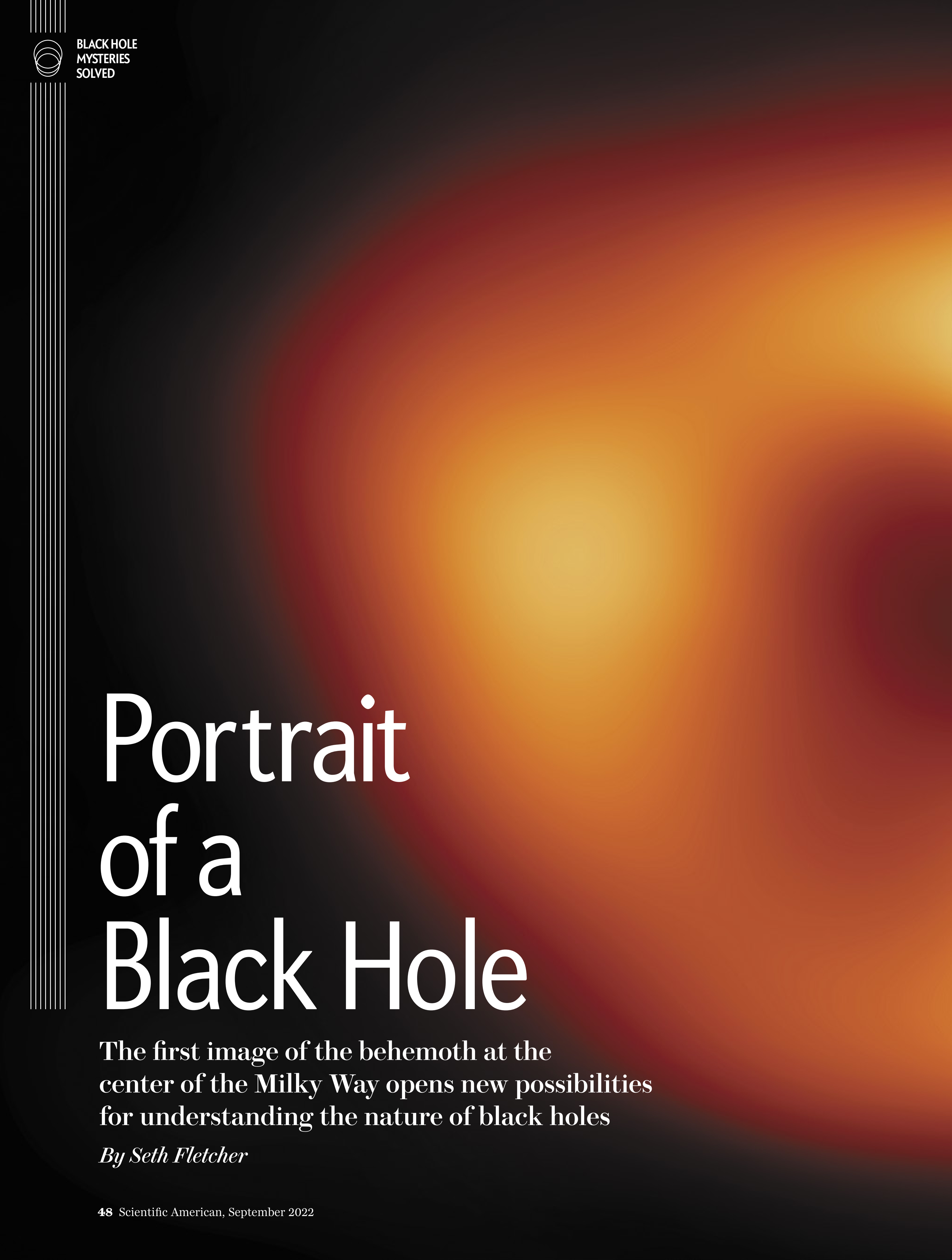
The other way to divine a holographic description is by looking for clues from the properties that such a description should have. This approach is part of the standard practice of science—use data to construct a theory that reproduces the data and hope it makes novel predictions as well. In this case, however, the data themselves are also theoretical. They are things we can reliably calculate even without a complete understanding of the full theory, just as we can calculate the trajectory of a baseball without using quantum mechanics. The idea works as follows: we calculate various things in classical cosmology, maybe with a little bit of quantum mechanics sprinkled in, but we try to avoid situations where quantum mechanics and gravity are equally important. This forms our theoretical data. For example, Hawking radiation is a piece of theoretical data. And what must be true is that the full, exact theory of quantum cosmology should be able to reproduce this theoretical datum in an appropriate regime, just as quantum mechanics can reproduce the trajectory of a baseball (albeit in a much more complicated way than classical mechanics).

Leading the charge in extracting these theoretical data is a powerful physicist with a preternatural focus on the problems of quantum cosmology: Dionysios Anninos of King's College London has been working on the subject for more than a decade and has provided many clues toward a holographic description. Others around the world have also joined the effort, including Edward Witten of IAS, a figure who has towered over quantum gravity and string theory for decades but who tends to avoid the Wild West of quantum cosmology. With his collaborators Venkatesa Chandrasekaran of IAS, Roberto Longo of the University of Rome Tor Vergata and Geoffrey Penington of the University of California, Berkeley, he is investigating how the inextricable link between an observer and the cosmological horizon affects the mathematical description of quantum cosmology.

Sometimes we are ambitious and try to calculate theoretical data when quantum mechanics and gravity are equally important. Inevitably we have to impose some rule or guess about the behavior of the full, exact theory in such instances. Many of us believe that one of the most important pieces of theoretical data is the amount and pattern of entanglement between constituents of the theory of quantum cosmology. Susskind and I formulated distinct proposals for how to compute these data, and in hundreds of e-mails exchanged during the pandemic, we argued incessantly over which was more reasonable. Earlier work by Eva Silverstein of Stanford, another brilliant physicist with a long track record in quantum cosmology, and her collaborators provides yet another proposal for computing these theoretical data.

The nature of entanglement in quantum cosmology is a work in progress, but it seems clear that nailing it will be an important step toward a holographic description. Such a concrete, calculable theory is what the subject desperately needs, so that we can compare its outputs with the wealth of theoretical data that are accumulating from scientists. Without this theory, we will be stuck at a stage akin to filling out the periodic table of elements without the aid of quantum mechanics to explain its patterns.

There is a rich history of physicists quickly turning to cosmology after learning something novel about black holes. The story has often been the same: we've been defeated and humbled, but after licking our wounds, we've returned to learn more from what black holes have to teach us. In this instance, the depth of what we've realized about black holes and the breadth of interest in quantum cosmology from scientists around the world may tell a different tale. SA

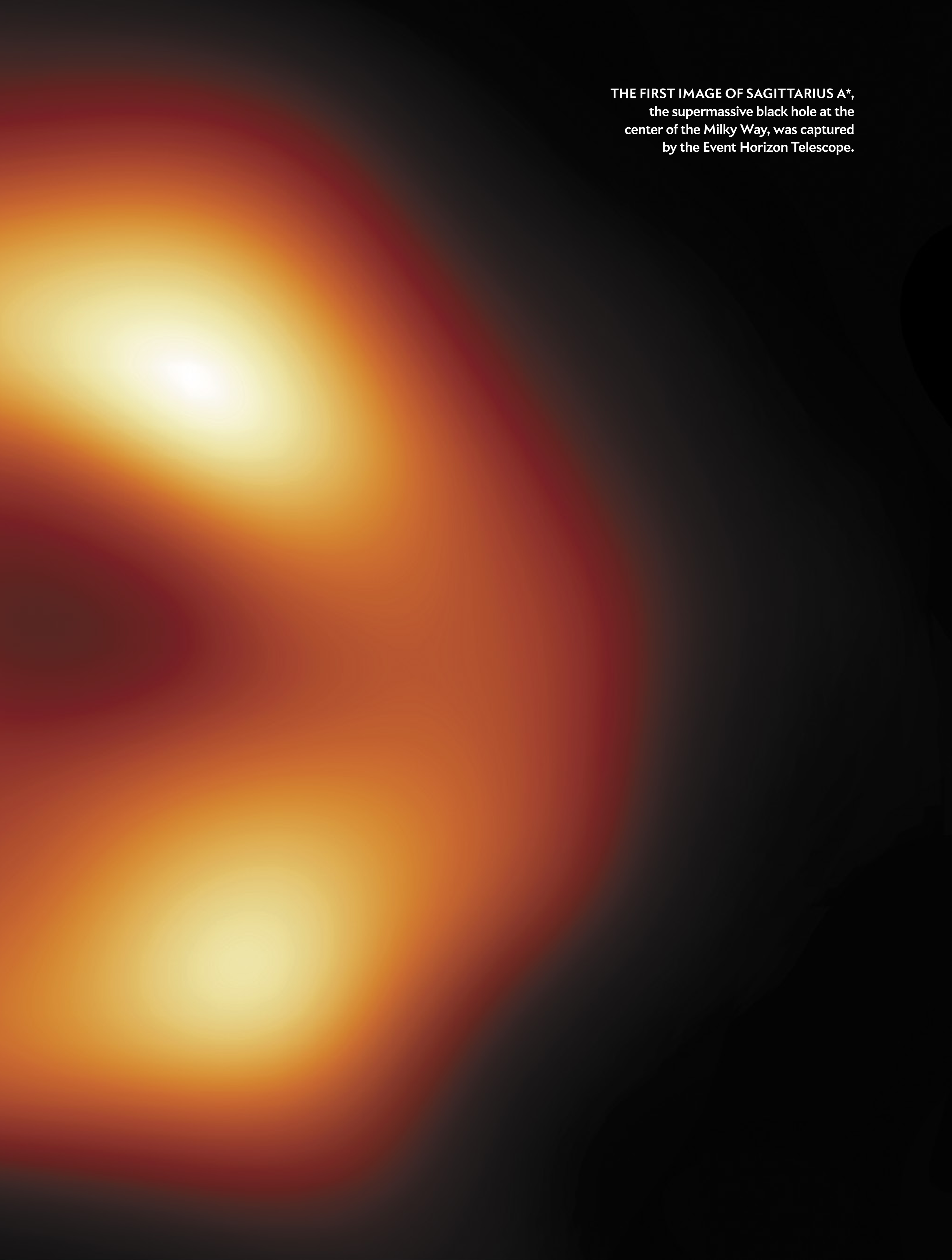


BLACK HOLE MYSTERIES SOLVED

Portrait of a Black Hole

The first image of the behemoth at the center of the Milky Way opens new possibilities for understanding the nature of black holes

By Seth Fletcher



THE FIRST IMAGE OF SAGITTARIUS A*, the supermassive black hole at the center of the Milky Way, was captured by the Event Horizon Telescope.

Seth Fletcher is chief features editor at *Scientific American.* His book *Einstein's Shadow* (Ecco, 2018) is about the Event Horizon Telescope and the quest to take the first picture of a black hole.

DEEP IN THE HEART OF THE MILKY WAY, STRANGE THINGS HAPPEN. THIS IS A PLACE where stars slingshot around apparently empty space at an appreciable fraction of the speed of light. Scientists have long thought that only a supermassive black hole could explain the stars' movements, but until this year, they hesitated to say that outright. For example, when astronomers Reinhard Genzel and Andrea Ghez shared a portion of the 2020 Nobel Prize in Physics, their citation specified that they were awarded for "the discovery of a supermassive compact object at the centre of our galaxy," not the revelation of a "black hole." The object is known as Sagittarius A* ("Sagittarius A star").

This spring, however, the astronomers behind the Event Horizon Telescope (EHT) settled the matter by unveiling the first image of a supermassive black hole at the center of the Milky Way. It wasn't the first picture of a black hole this collaboration had captured—that was the iconic image of M87*, which they revealed in April 2019. But it was the one they wanted most. Sagittarius A* is our own private supermassive black hole, the still point around which our galaxy revolves.

Black holes trap everything that falls in, including light, so they are, in a very real sense, unseeable. But they warp spacetime around them so severely that, when they are illuminated by glowing streams of infalling matter shredded in their gravitational grip, they cast a "shadow." The shadow is about two and a half times larger than a black hole's event horizon, the boundary in spacetime through which nothing that passes can ever return.

The EHT captured images of this shadow using a technique called very long baseline interferometry (VLBI), which combines radio observatories on multiple continents to form a virtual Earth-size telescope, an instrument with the highest resolution in all of astronomy. In April 2017 the EHT collaboration spent several nights pointing that virtual instrument at Sagittarius A* and other supermassive black holes. The scientists then spent years analyzing the raw data and converting them into an image.

Part of the reason it took so long was the global devastation of the COVID pandemic. But the bigger challenge was that Sagittarius A* is constantly changing. The observatory's previous target, M87*, the black hole at the heart of the galaxy Messier 87 (M87), is so huge that the matter swirling around it takes many hours to complete a full orbit. Practically speaking, that means you can stare at it for a long time, and it will scarcely change. Sagittarius A* is more than 1,000 times less massive, so its appearance changes about 1,000 times faster, as matter moves in tighter, quicker orbits around the black hole. Katie Bouman, a California Institute of Technology computer scientist and astronomer who co-leads the EHT's imaging working group, said that matter orbits Sagittarius A* so quickly that it changes "minute to minute." Imagine taking a time-lapse photograph of a speeding bullet—it's not easy.

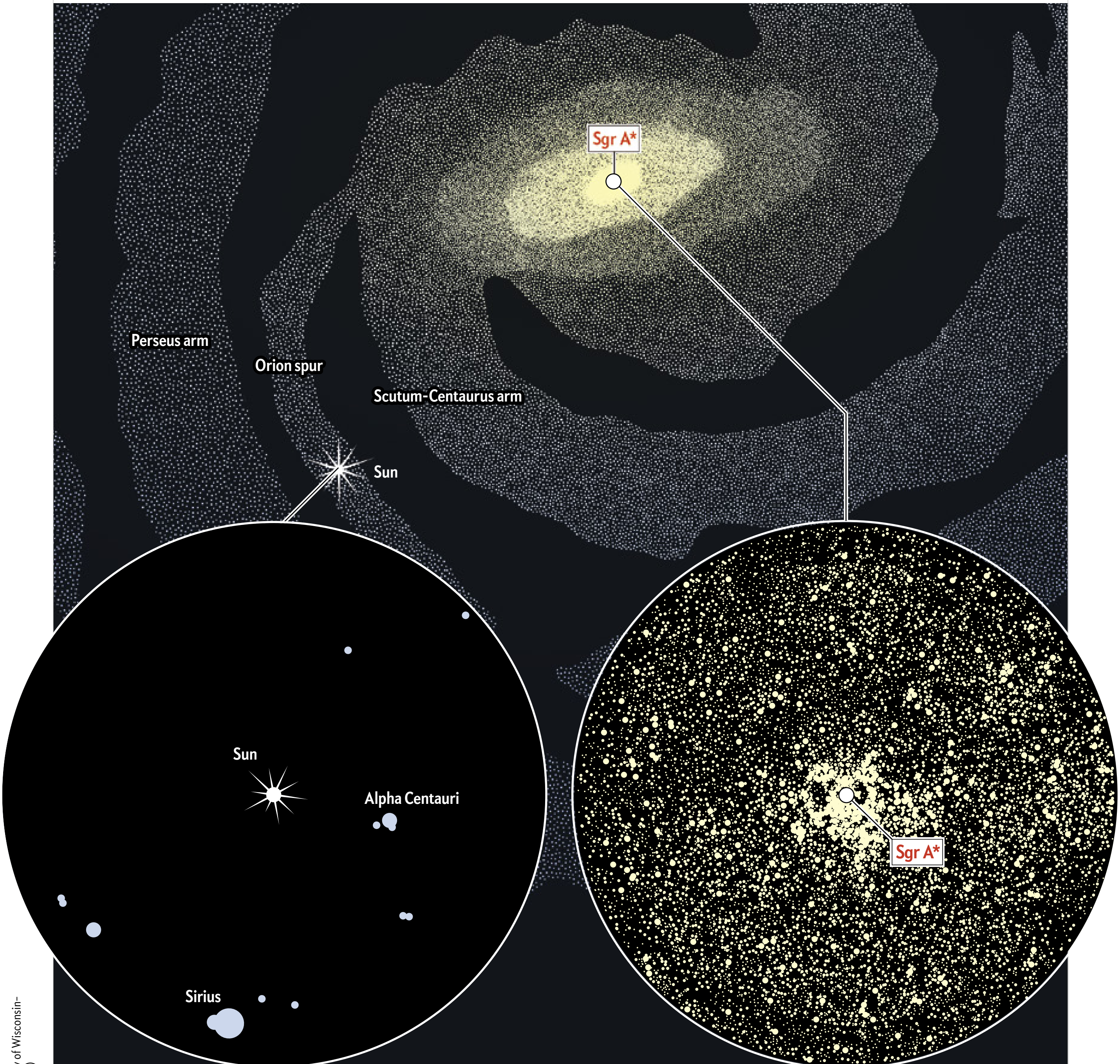
If Sagittarius A*'s mercurial nature made it hard to see, it also makes it an ideal laboratory for understanding black holes and Einstein's general theory of relativity, his hallowed theory of gravity. Through decades of study with all manner of telescopes, astronomers already knew Sagittarius A*'s basic measurements (its mass, diameter and distance from Earth) to great accuracy. Now, at last, they've gained the ability to watch it evolve—to watch as it feeds on flaring, flashing streams of matter—in real time.

SCIENTISTS STARTED TO SUSPECT THAT A BLACK HOLE LURKED in the heart of the Milky Way in the early 1960s, not long after the discovery of active galactic nuclei—extremely bright regions at the cores of some faraway galaxies illuminated by voraciously feeding supermassive black holes. From our perspective here on Earth, active galactic nuclei are a thing of the past—we see them only in the distant, ancient universe. Where did they all go? In 1969 English astrophysicist Donald Lynden-Bell argued that they didn't go anywhere. Instead, he said, they just went to sleep. Dormant supermassive black holes, he

EHT Collaboration (*preceding pages*)

Our Black Hole

The Milky Way's central supermassive black hole, Sagittarius A*, is roughly 27,000 light-years from Earth, at the core of the dense, chaotic region known as the galactic center. With a diameter roughly equivalent to the planet Mercury's orbit around our own sun, it's not exactly small, but it's so far away that to us, it appears to be the size of a doughnut on the moon.



THE SOLAR NEIGHBORHOOD
Our sun occupies a spot on a relatively distant arm of the Milky Way—about two thirds of the way out from the galactic center—and our local neighborhood is relatively sparse, with just 14 known stars within 10 light-years of the sun.

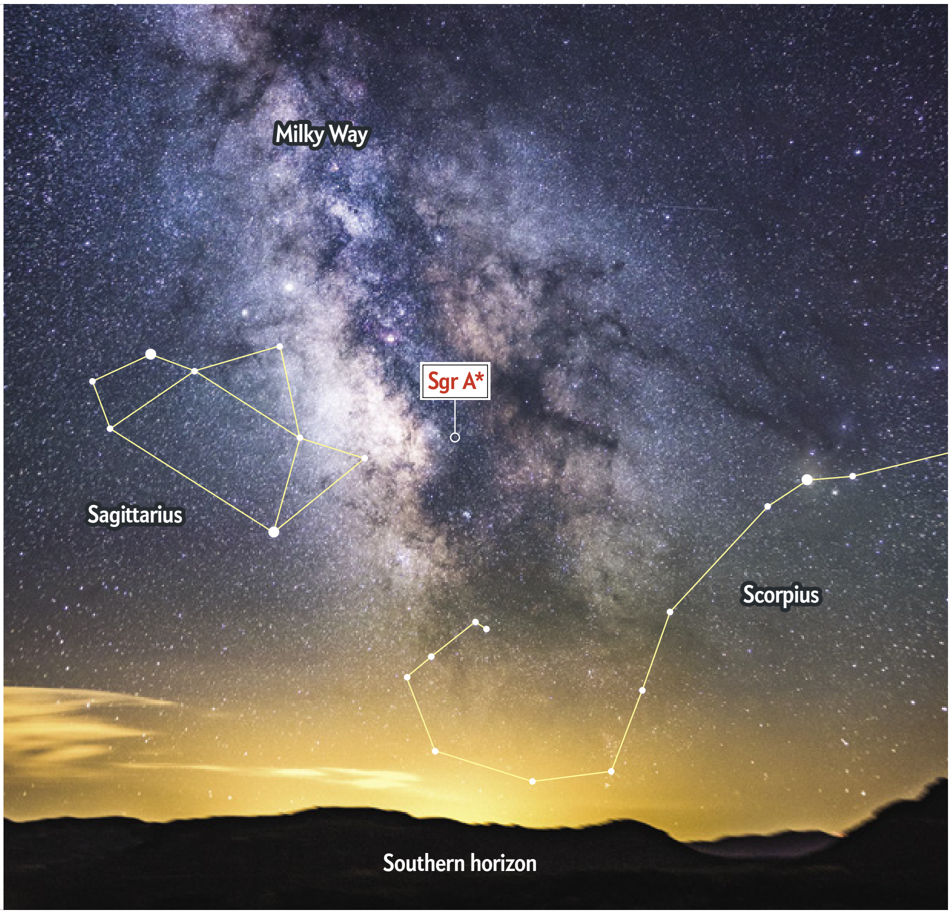
THE GALACTIC CENTER
The central region of the Milky Way is a profoundly crowded place. Millions of stars lie within 10 light-years of Sgr A*. One percent of those stars are pictured here.

Source: Bob Benjamin, University of Wisconsin–Whitewater (*Milky Way structure*)

Graphic by Katie Peek

The Center of Our Galaxy

Sagittarius A* and the greater galactic center reside near the constellation Sagittarius. One of the major challenges the Event Horizon Telescope has faced is finding times when Sagittarius A* is "up"—above Earth's horizon—for all the observatories in the worldwide array, which are spread across continents and are located in both hemispheres.



Eloi Omella/Getty Images (*Milky Way photograph*)

predicted, are slumbering all around us in the hearts of nearly all spiral galaxies, including our own.

In 1974 American astronomers Bruce Balick and Robert Brown pointed radio telescopes in Green Bank, W.Va., at the center of the Milky Way and discovered a dim speck they suspected was our galaxy's central black hole. They found it in a slice of sky, known as Sagittarius A, within the constellation Sagittarius. Radiation from the new source was lighting up—or "exciting"—surrounding clouds of hydrogen. Brown borrowed from the nomenclature of atomic physics, in which excited atoms are marked with an asterisk, and named the new-found speck Sagittarius A*.

For the next two decades radio astronomers kept gradually improving their view of Sagittarius A*, but they were limited by a lack of suitable telescopes, relatively clunky technology (think reel-to-reel magnetic tape) and the inherent difficulty of looking into the crowded galactic center.

Sagittarius A* is concealed by a multilayered veil. The first layer is the galactic plane—27,000 light-years' worth of stars, gas and dust that blocks visible light. Radio waves sail through the galactic plane unimpeded, but they're obscured by the veil's second layer—the scattering screen, a turbulent patch of space where density variations in the interstellar medium knock radio waves slightly off course. The final layer concealing Sagittarius A* is the infalling matter surrounding the black hole itself. Peering through that barrier is a bit like peeling off an onion's skins. The outer layers of matter emit longer-wavelength light—the same wavelengths VLBI traditionally works with. Making VLBI work with shorter-wavelength light would enable closer-in views approaching the black hole's event horizon, but it was a major technological challenge.

For a while, astronomers using other techniques besides VLBI had more success, steadily gathering indirect evidence that Sagittarius A*'s "speck" was actually a seething supermassive black hole. In the 1980s physicist Charles Townes and his colleagues showed that gas clouds in the galactic center were moving in ways that made sense only if they were under the influence of some great, unseen gravitating mass. And in the 1990s Ghez and Genzel independently began tracking the orbits of giant blue stars in the galactic center, mapping their motion around a heavy but hidden pivot point.

Meanwhile the situation for radio astronomers improved. In the late 1990s and early 2000s a new generation of short-wavelength radio telescopes started to come online—telescopes that, if augmented with lots of bespoke equipment, could participate in VLBI observa-

Graphic by Katie Peek

tions at the microwave frequencies thought to shine from the edge of Sagittarius A*'s shadow. At the same time, the computing revolution that led to solid-state hard drives and smartphones in every pocket vastly increased the amount of data that each observatory in a network of radio telescopes could record and process.

In 2007 a small precursor to the EHT took advantage of these trends and used a trio of telescopes in Hawaii, California and Arizona to pierce the veil surrounding Sagittarius A*. The result was far from an image, but the project saw *something*—presumably, light from the long-sought shadow.

The first prediction of black hole shadows came in 1973, when physicist James Bardeen showed that a black hole in front of a bright background would produce a silhouette. He decided that "there seems to be no hope of observing this effect." In 2000, however, astrophysicists Heino Falcke, Fulvio Melia and Eric Agol demonstrated that a microwave-gathering, Earth-size radio telescope should be able to see the shadow of Sagittarius A*.

Half a decade afterward, a few dozen of the astronomers and astrophysicists laboring in this obscure corner of astronomy agreed on the formal goal of building a virtual planet-scale radio telescope to observe that shadow. The first official kickoff meeting for the project occurred in January 2012, and the Event Horizon Telescope was born.

Five years later, after growing into a collaboration of more than 200 scientists with eight participating observatories across the globe, the EHT took its first realistic shot at seeing the shadow of Sagittarius A*. Over the course of 10 days in April 2017, telescopes in North America, South America, Hawaii, Europe and Antarctica collectively zoomed in on the galactic center and other black holes, gathering 65 hours of data on 1,024 eight-terabyte hard drives, which were shipped to supercomputer banks in Massachusetts and Germany for correlation. Five years after *that,* the elated EHT researchers showed the world that their experiment worked.

THE DAY THE EHT COLLABORATION REVEALED SAGITTARIUS A*'S image, the *Astrophysical Journal Letters* published a special issue devoted to the new results. In six technical papers, the scientists presented a multidimensional portrait of our black hole.

The EHT image confirmed the basics. We've long known that Sagittarius A* is about 27,000 light-years away. Years spent tracking the orbits of stars around Sagittarius A* with infrared telescopes had already given astronomers an accurate measure of the black hole's mass—the equivalent of roughly four million suns. Plug those two numbers (distance and mass) into equations derived from general relativity, and you can calculate the expected size of the black hole's shadow. Sure enough, the image matches the prediction. The shadow has a diameter of 52 micro arc seconds, which means that to us here on Earth it is, in the astronomers' formulation, the size of a "doughnut on the moon." After seeing the shadows of both Sagittarius A* and M87*—black holes that differ in mass by three orders of magnitude—the scientists concluded that the phenomena are "universal features of black holes."

The EHT observations, combined with simultaneous monitoring by the Chandra and Nu-STAR x-ray telescopes and other instruments, are starting to settle long-standing questions about Sagittarius A*'s environment. By measuring the spectra of light shining from the object—that is, the light broken up into its constituent frequencies—astronomers long ago determined that the matter orbiting the black hole is a diffuse gas of electrons and protons. We now have a much better idea of where that matter comes from. Observations from the Chandra x-ray telescope show that the black hole pulls that matter from the atmospheres of stars orbiting it. Not that it pulls very much. Sagittarius A* is on a starvation diet—less than 1 percent of the stuff captured by the black hole's gravity ever makes it to the event horizon. That explains why the black hole is so dim. Despite being four million times more massive than our sun, Sagittarius A* is only 100 times brighter.

It wasn't always so faint. As recently as 60 or 70 years ago, Sagittarius A* appears to have gone on a feeding binge, a burst of activity that left "light echoes"—light bouncing off nearby clouds of dust and gas—that astronomers have detected using x-ray telescopes. And it still has its active moments. On April 11, 2017, Sagittarius A* emitted a bright x-ray flare. The cause, most likely, was the twisting and recombining of magnetic fields inside the matter orbiting the black hole—the same basic dynamic that causes solar flares in our own star. Directly observing these flares is a major goal for future campaigns.

There's much more to learn about Sagittarius A*. For example, the EHT observations show that, like everything else in space, the black hole is spinning—but we don't know how fast. Future observations also aim to show exactly how the black hole eats infalling matter, and, with luck, make movies of the black hole evolving over time.

The first EHT picture of Sagittarius A* is just the beginning, but it does tell us what the object is not. The presence of a distinctive shadow means Sagittarius A* has an event horizon—the defining feature of a black hole. That means we finally know it's not a really, really, really dense star, or a wormhole, or a naked singularity (a point of infinite density unconcealed by an event horizon), or any of the other exotic oddities theorists have proposed over the years. It's nothing stranger than a supermassive black hole—still a pretty strange thing indeed—now brought within view, closer to revealing its secrets.

FROM OUR ARCHIVES

Black Holes and the Information Paradox. Leonard Susskind; April 1997.
Burning Rings of Fire. Joseph Polchinski; April 2015.
The Black Hole Test. Dimitrios Psaltis and Sheperd S. Doeleman; September 2015.
Escape from a Black Hole. Steven B. Giddings; December 2019.

scientificamerican.com/magazine/sa

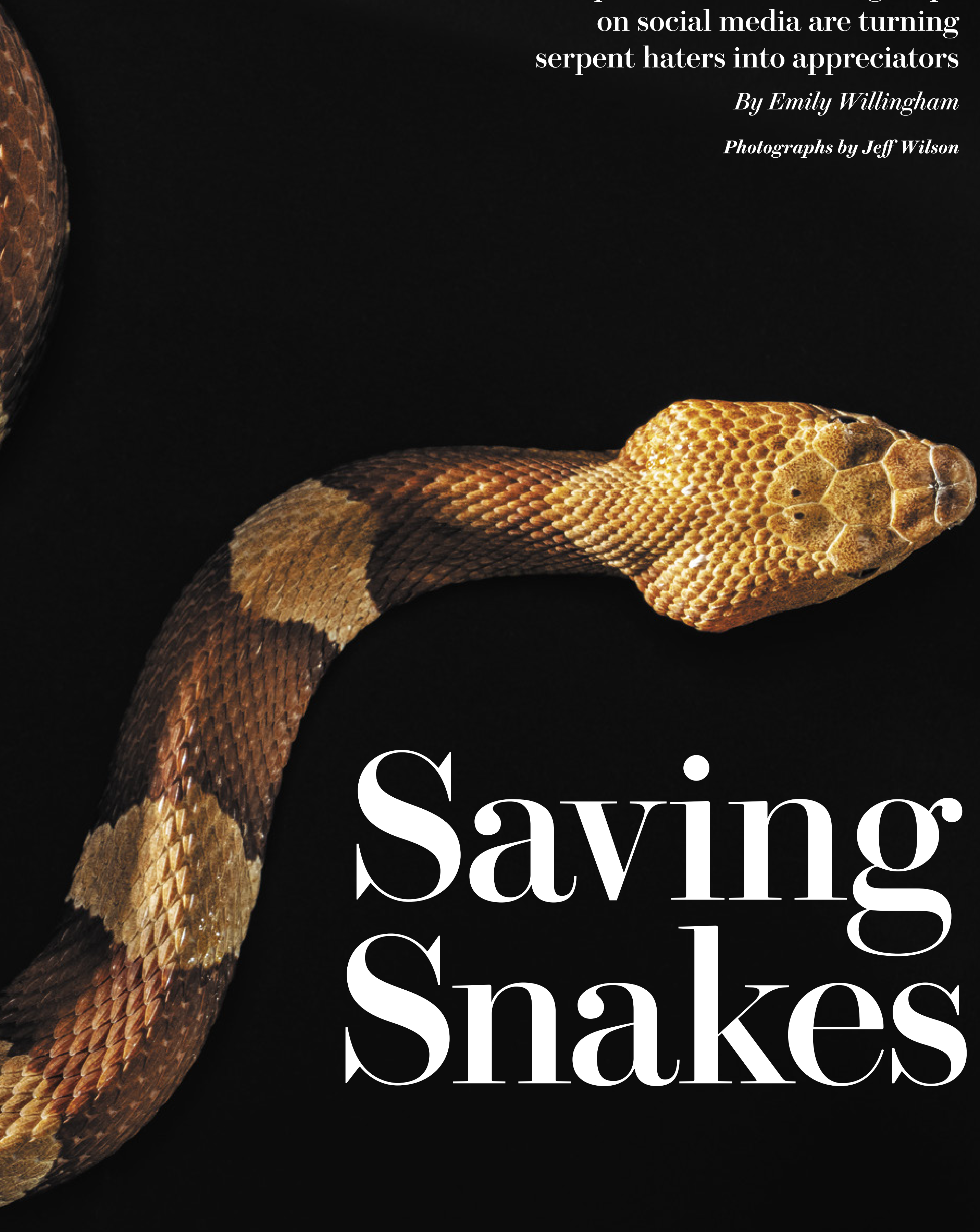
EASTERN COPPERHEAD (*Agkistrodon contortrix*) is one of 11 venomous snake species found in Texas.

Saving Snakes

Species-identification groups on social media are turning serpent haters into appreciators

By Emily Willingham

Photographs by Jeff Wilson



Emily Willingham is a science writer and author based in Texas. Her latest book is *The Tailored Brain* (Basic Books, 2021).

WHEN ALLISON BAKER MOVED TO WHAT SHE CALLS "SNAKE HEAVEN," a home on 2.5 acres just outside of Dallas–Fort Worth, Tex., her greatest fear was a dangerous encounter between her young children and one of heaven's residents. Baker's anxiety was understandable. After all, Texas is one of the snakiest states in the nation, with more than 80 species, 11 of them venomous. And the previous homeowners had found venomous snakes on the property, including a cottonmouth coiled by the pool. It wasn't long before she had her own run-ins with the slithering creatures—including a bite she received from a copperhead while doing yardwork.

Yet despite her initial trepidation, Baker, 44, has undergone an attitude change since moving into the new place. "I knew better than to dig in a pile of leaves," she says of her brush with the copperhead. "I didn't blame the snake for it and got a shovel and flipped the snake out of there," relocating the animal rather than dispatching it. Although most people would probably have gone to the emergency room, Baker's bite happened mid-pandemic. So after a telehealth consult, she took some antihistamine and rode out the fairly mild symptoms she experienced. "It's okay," she says casually. "I have a scar."

What force could drive such a dramatic shift in perspective? Baker credits, of all things, a Facebook group, one whose mission it is to educate members about snakes. Although the social media giant has a bad reputation for doing everything wrong in public health and politics, it turns out to be a powerful tool for saving snake lives. It's not just Facebook. Wildlife enthusiasts are co-opting various social media platforms to build communities that promote accurate snake information and slay viral myths. Through these efforts they are converting even the most committed snake haters into ardent snake appreciators whose newfound regard for these misunderstood creatures often spreads to family, friends and neighbors. One by one, the snakes are living to slither another day.

FEAR FACTOR

IT WAS CHICKENS that led Baker to the snake ID groups. Having chickens "couldn't be a more down-home, country, just warm feeling, so domestic and wonderful until you open the doors and there's a five-foot rat snake with an egg down it," she says. "That domestic warm feeling immediately evaporates into pure panic." A common reaction people have on encountering a snake is to kill it—regardless of whether it actually poses a threat. Wondering if there was another way, Baker turned to Facebook.

Herpetologist Mark Pyle created the Facebook group

"What kind of snake is this? North Texas Educational Group" in 2013 after years of trying more conventional snake-conservation outreach. Pyle, 48, lives in Hood County, Texas, and is the current president of the Dallas–Fort Worth Herpetological Society. In his earlier outreach efforts, he never felt like he was getting any traction "because you only have a few moments with each person." Pyle really wanted to help people more than snakes. "If you can help people with some knowledge about a subject, the conservation end of it takes care of itself," he says. "You can't care about or love something you don't know the first thing about."

Whereas other social media ID groups encompass huge areas, from entire continents to the entire planet, Pyle went local, focusing on the snakes he's most familiar with. That way, he reasoned, "I can actually help if someone has a snake in their backyard." He hoped his regional approach would serve as a template for other local efforts.

Today Pyle's group has more than 176,000 members eagerly exchanging information about the region's venomous rattlesnakes, copperheads, cottonmouths and coral snakes, as well as its nonvenomous rat snakes and water snakes, among other harmless species. "This group has been the first time in my life that I think I'm making a real difference," he says. Other regional groups that have formed include a statewide Texas ID and Central Texas Snake ID, which has more than 43,000 members and is run by a snake-relocation service near San Antonio. Facebook features dozens of other groups, too, mostly in the southern and southwestern states where most snakes live, covering regions as niche as Southside Atlanta.

BUILDING COMMUNITY

THE PREMISE OF THE GROUPS is simple. A member uploads an image of a snake they want identified, and within minutes an expert administrator responds. One unbreakable rule of the pages is that users have to keep their guesses to themselves. Only IDs made with

MARK PYLE created a Facebook group to educate people about snakes in North Texas.

certainty are allowed. For Pyle, this rule is so crucial that he once muted his own daughter for guessing. It can be a matter of safety, especially if someone says a snake is nonvenomous when it isn't.

Admins may be snake experts, like Pyle, or amateur "snake nerds." Jon Farris, 38, a quality-control manager in Waco, Tex., helps to oversee the Central Texas Snake ID group. His knowledge of snakes is all self-taught—"I've always liked them," he says—and after a few years of establishing his bona fides with accurate IDs on the boards, he eventually became an administrator. He spends a lot of time helping panicked newcomers, who tend to think every snake they come across is a cottonmouth that they need to kill. Usually it's a case of mistaken identity, and what they have instead is one of the nonvenomous water snakes. The distinction, long-term members of these groups can tell you, is that a diamondback water snake, or DBWS (*Nerodia rhombifer,* nonvenomous) in their parlance, has vertical lines on the upper jaw and close-set eyes, giving it an appearance that superfans lovingly describe as "goofy." Cottonmouths (*Agkistrodon piscivorus,* venomous), in contrast, have hooded eyes on the sides of their heads and no vertical upper jaw lines. They definitely do not look "goofy."

As members become more familiar with the snakes in their area through participation in the ID groups, they find themselves better able to respond appropriately when they discover one at home. International flight attendant Sheryl Guth, 62, had four snake encounters in a single day that all had positive outcomes thanks to the North Texas group. Had she not joined it four years earlier, the final encounter of that snakeful day, with a rat snake wrapped around her door handle, would probably have ended poorly for the snake. "The movement was what caught my eye, but I was able to ID it based on what I've learned from being on that page," she recalls. "The rest of the family was freaking out, and I was like no, no, no, he's okay, probably going up to that bird nest over the door and get the eggs and go on its way."

The education Guth has gained from the identification page also got her through the time she found a snake in her bathroom. "He was kind of a grumpy snake, and everybody was going, 'Omigod, omigod, it's a water moccasin, kill it!' " she recollects. A water moccasin (another name for a cottonmouth) would be cause for concern, but she knew from the page to check

for the vertical bars on the upper jaw—a feature of the nonvenomous plain-bellied water snake as well as of the DBWS—and there they were. Instead of killing the snake, they used a broom to usher it outdoors.

Converts to snake conservation proselytize family, friends and neighbors hardened against the animals, talking them into showing mercy to a snake until they can get an ID. Betsy Patel, 39, lives right outside of Denton in North Texas. One day she'd sent a relative a picture of a rough earth snake inside her home. The relative said, "Oh, that's a good one, keep it in the house" and referred her to the snake ID group. Although Patel decided against keeping the tiny, nonvenomous visitor indoors—"we shoeboxed him and put him in the yard"—she in turn has urged other family and friends to join the group.

As a family, the Patels have banded together to let other snakes live, too: a garter snake seen in a garden was left undisturbed; a rat snake spotted in a water barrel—one of many unexpected places where this adventuresome species turns up—was simply netted out. Even at a friend's pool party, when one of the kids found a garter snake, the initial freak-out turned to friendliness. "A boy reached in and said, 'Oh, I love these,' and they all got to pet it," Patel recalls. One family, four snake lives saved.

Sometimes, though, a snake submitted to a group for identification is venomous or injured and warrants professional intervention. A benefit of belonging to a hyperlocal snake-identification group is that members may be able to find a nearby expert who can relocate a problematic snake or take it to a local rehabilitation center, services some page administrators themselves offer. Farris says he's been doing local relocations for free for a couple of years, mostly rattlesnakes and copperheads. On more than one occasion he's found himself under a house or a trailer in the wee hours of darkness tracking down a copperhead or rattler that needs to be moved. "I put my money where my mouth is there," he says about following his mission to help on the ground if someone has a snake in their yard.

Exactly how big an impact these social media outreach efforts are having on snake populations is unclear. According to Texas's state herpetologist, Paul Crump, counting snakes is tough because they are secretive animals. He has little doubt, though, that these educational groups are beneficial and have "saved a number of snakes from meeting an untimely end." A

NONVENOMOUS diamondback water snake, *Nerodia rhombifer* (*left*), is often mistaken for the venomous cottonmouth or water moccasin, *Agkistrodon piscivorus* (*right*).

look at activity on the Central Texas Snake ID page gives a single-day snapshot of how snakes fare among converts. As December 31 turned over to the new year, 14 people posted snake pictures, representing sightings from throughout the heart of Texas. Of these snakes, two were venomous—one copperhead and one cottonmouth. Six of the 12 nonvenomous animals were rat snakes, including one wrapped hoselike around an actual water hose and another actively investigating a rocking chair on a front porch, alive and slithering. Only one of the 14 ended up dead, a DBWS killed by a group member's neighbor, who was convinced it was a copperhead and now knows better.

FROM PHOBIC TO FASCINATED

IT'S NOT JUST SNAKES that benefit from these groups. Some of the most fanatical snake enthusiasts often start out, like Baker did, as the most fearful, Pyle says. They are part of a large club of people who are afraid of snakes. Indeed, studies suggest that snakes are among the most commonly feared animals.

Researchers have long sought to understand the roots of this aversion, theorizing that primates might have evolved an innate fear in response to being preyed on by constrictorlike snakes. Human infants do pay special attention to images of snakes and snakelike movements, though without necessarily being scared. It may be that culture turns an inborn human ability to detect snakes into a fear.

If the fear is learned, perhaps it can be unlearned. "I've felt that fear and fascination are kind of tied together in the human psyche, kind of the same thing," Pyle says based on his experiences with people who are scared of snakes. "If you put the knowledge there, that turns fear into fascination." Yusuf Danawala made that switch so distinctly after joining the North Texas group that even his dreams changed. A neighbor directed him to the page after a rat snake turned up on Danawala's doorstep and freaked him out, a common reaction to rat snakes, which can reach lengths of 10 feet. Danawala began visiting the page every day and testing his identification skills. "It turns into a game: Can I identify it myself?" says Danawala, 42, a cybersecurity sales engineer in the North Dallas area.

Snake ID became therapy for him. "You're scrolling page after page of snake pictures, getting used to seeing them, getting desensitization and knowledge." Before he engaged with the group, "I would dream about a snake attacking me, or I am running away from it," he says. But now in his dreams, he'll be stepping over a snake and think, "Oh, that's a rat snake or that's a coral" and just walk away. Now he's even a fan of a slender, lime-colored species, the rough green snake (*Opheodrys aestivus,* nonvenomous). "They have this adorable smile on their face," he says.

Allison Hollier, 56, a geographic information systems analyst in Burleson, Tex., had nightmares every night for the six weeks that a six-foot broad-banded water snake (*Nerodia fasciata,* nonvenomous) occupied her koi pond before she could have it relocated. Then she joined the North Texas group at a friend's suggestion, and her snake dreams became "nonexistent," she says. The desensitization and understanding she gained by looking at the page every day "does work," she says. "I'm living proof."

Her words echo what psychologist András Norbert Zsidó of the Institute of Psychology at the University of Pécs in Hungary has found in his studies of snake fears. "The exposure in such groups has two key factors: habituation and knowledge," he says. Group members can encounter the object of their fear while being in control of the encounter, he explains, which is important in exposure therapy.

"The anxiety and fear the person feels slowly subside; the person gets used to the object. This is what we call habituation," Zsidó says. "People in such groups can learn a lot about snakes and various species, and that knowledge in itself could also help lower the fear." The familiarity inoculates them against the fear, which may then become fascination.

Adults who show fascination instead of fear may be creating a generation habituated to snakes. Patel and her daughter, Eleanor, who is eight, scroll through the North Texas group a few times a week to try to ID the animals. Eleanor's favorite is the western diamondback rattlesnake (*Crotalus atrox,* venomous) because "they have a really cool pattern." What would she do if she encountered one in person? "I would go inside," she says. "I would just leave it alone."

Lori Pollitt, 61, lives between a nature preserve and a golf course in Collin County, Texas. She says that when the city comes out to do flood cleanup, they call her home "the snake house" because at every visit, they seem to find a snake or two.

At first, she didn't find that appellation very reassuring—"after hearing that, I was ready to sell the house and move out"—but since joining the local Facebook snake group, she's come around. She has a favorite snake on the property, a ribbon snake (*Thamnophis saurita,* nonvenomous) that she believes she and her family have been seeing around for several years, and she even describes some of the snakes in her yard as "friendly."

Pollitt's eight-year-old granddaughter, Claire, shares her newfound fascination. The two of them often look through the snake group page "just for fun. We just sit there and scroll." When asked by e-mail which snake is her favorite, Claire sent back a drawing of a hognose, which snake fans call the "drama noodle" because of its theatrical efforts to appear unapproachable, calling that her favorite "because when you scare it, it looks funny." SA

FROM OUR ARCHIVES

The Promise of Virtual Reality. Claudia Wallis; February 2019.

scientificamerican.com/magazine/sa

WESTERN RAT SNAKE (*Panthero-phis obsoletus*) poses no threat to humans but is commonly confused with the venomous cottonmouth.

METEOROLOGY

FORECASTING ATMOSPHERIC RIVERS

Knowing when torrents of rain will strike can save property and lives

By F. Martin Ralph

Illustration by Mark Ross

F. Martin Ralph is a research meteorologist and founding director of the Center for Western Weather and Water Extremes at the Scripps Institution of Oceanography, part of the University of California, San Diego.

I WAS EATING BREAKFAST ON A MONDAY MORNING AT SEARS FINE FOOD IN DOWNTOWN SAN FRANCISCO, casually watching the local five-day weather forecast on a television screen behind the counter. A little symbol along the bottom showed a happy-looking sun for the rest of the day. Wednesday had a friendly-looking cloud and a few raindrops, and Thursday had a dark, threatening cloud with heavier drops. I knew Thursday's conditions would be much rougher than the symbol conveyed. I had been studying detailed satellite data and weather models, and they indicated that a major atmospheric river (AR) was likely to hit the city. The symbol was completely inadequate for communicating the threat of the approaching storm.

ARs are essentially rivers of water vapor in the sky that are pushed along by strong, low-altitude winds, sometimes at hurricane speeds. The meteorological community formally defined them only in the early 2010s, after improved satellite imaging and science revealed how these storms can form far out over the remote ocean. They can grow to 2,000 miles long, 500 miles wide and two miles deep by the time they strike the western coasts of continents. An average AR brings far greater rainfall than a typical rain or thunderstorm in those parts of the world, transporting enough vapor to equal 25 times the flow rate of the Mississippi River where it pours into the Gulf of Mexico.

These storms can produce disastrous flooding, including the biggest floods that some areas may see in a century. They can occur in families—a series of storms, as if rolling in on a treadmill. Several times a year they pummel the western coasts of the U.S., Canada, Europe, Africa, South America and New Zealand. They can also reach far inland: the raging terrestrial rivers that tore apart roads in Yellowstone National Park and forced the park to close this past June were fueled in large part by a remarkably strong AR.

ARs are not always destructive; sometimes they bring welcome rain to parched regions. They can beneficially boost snowpack and help fill natural and human-made water reservoirs. It's hard to know more than a few days ahead where exactly a storm will make landfall, however. As big as they are, they can be fickle because numerous forces can affect their progression, from ocean-surface temperatures to pockets of cold air aloft.

On the same day that the AR was slated to hit San Francisco, I was scheduled to present new insights into these storms at the 2016 American Geophysical Union meeting there. Struck by the inadequacy of the TV weather icons, I pledged to finish an intensity scale for ARs—a forecasting and communications tool that colleagues and I had been discussing for a while. Rather than a simplistic icon of a sun or cloud, I envisioned a square, yellow box on the screen for Thursday with a storm system's ranking in bold, black characters, similar to how hurricanes are characterized as categories 1 to 5. This ranking would allow weather forecasters, emergency planners, safety personnel and reservoir managers—as well as the public—to better prepare for potential flooding, transportation disruptions, downed power lines, debris flows or evacuations.

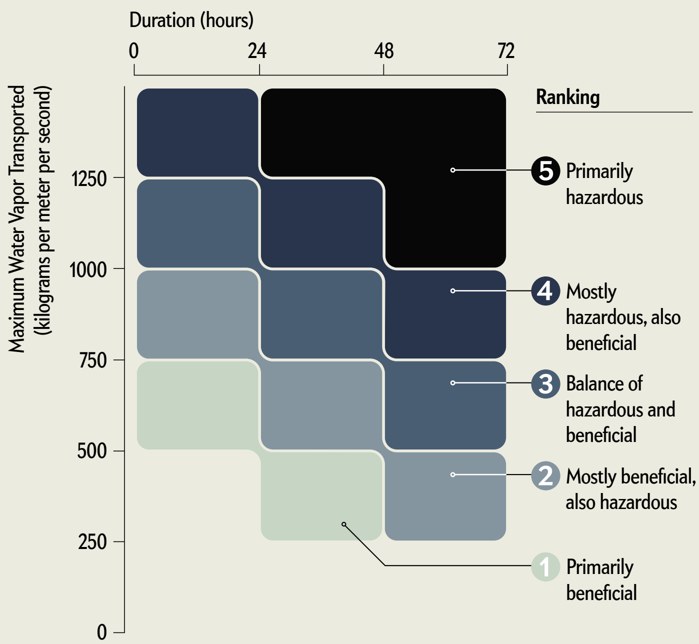
National Weather Service (NWS) forecasters provide the formal watches and warnings that trigger actions by numerous local officials. That week in San Francisco some of the experts were tuning in to a novel set of AR forecasting tools developed and provided by the Center for Western Weather and Water Extremes (CW3E) at the Scripps Institution of Oceanography, part of the University of California, San Diego, where I work. The tools track 10 or more variables, including the winds a few thousand feet aloft, along with horizontal movement of water vapor, that show the odds of an AR hitting a stretch of the coast. To make a clear and convincing ranking system, we would need to simplify those 10 variables into two quantities that represent the intensity and duration of an incoming AR.

The scale we devised runs from AR1 (primarily beneficial precipitation) to AR5 (primarily hazardous). The goal is to prompt people to pay close attention to the initial intensity level and any subsequent changes because strong ARs can wallop a coastal or inland mountain region with enormous amounts of rain or snow—for hours to days running—forcing ground personnel to regularly reassess actions.

Our team published the AR Scale in the *Bulletin of the American Meteorological Society* in 2019. A storm's ranking on the scale reflects a huge amount of work that happens behind the scenes every time scientists first see that an AR is forming. Case studies of several strong ARs that battered the U.S. West Coast over the past two years show how researchers and weather forecasters have gotten better at informing emergency planners and water managers on whether a storm will bring rain that is good for replenishing water supplies or crosses a threshold into floods and landslides.

The AR Intensity Scale

The scale that estimates an atmospheric river's strength and impact ranges from a low of 1 (primarily beneficial) to a high of 5 (primarily hazardous). Two factors affect the ranking: the amount of water vapor the storm is transporting horizontally through the atmosphere, and how long that transport lasts. Mild, AR1 storms can bring needed rain or snow to dry regions. Intense, AR5 storms can cause heavy flooding and associated damage. The rank is calculated for specific locations.



Source: "Scale to Characterize the Strengths and Impacts of Atmospheric Rivers," by F. Martin Ralph et al., in *Bulletin of the American Meteorological Society,* Vol. 100; February 2019 (*reference*)

With greater preparedness, officials can lessen risk to property and lives and know how to maximize water storage. A January 2021 AR that caused heavy landslides that severed cliffside roads along California's Big Sur coast—yet did not cause a single death—shows how well officials can use the latest forecasting science to observe these storms and manage consequences. The knowledge, forecasts and outcomes in this case illustrate the full potential of better forecasting and communication to help western coasts everywhere be ready for large storms.

SAVING LIVES

IN LATE JANUARY 2021 researchers could see that atmospheric patterns over the Pacific Ocean were setting up to bring another extreme event to the North American West Coast. The question was where an AR would land and how intense it would be. Tension among researchers rose quickly; along certain parts of the coast, as in Mediterranean climates globally, water is often a scarce resource, so residents, farmers and business owners all welcome rain. But of course, flooding rain can ruin agriculture, infrastructure and lives.

In the Pacific Northwest, rivers were still running high after weeks of heavy rains. The last thing people there needed was another wet storm. In California, which had been distressingly dry, a few inches of rain would bring needed relief, but a soaking could cause landslides on steep mountain slopes already stripped bare by wildfire.

On January 20 a team of atmospheric scientists, meteorologists, aircraft crews and staff at the Interagency Atmospheric River Reconnaissance Command Center based at CW3E decided to send data-gathering aircraft into the coalescing storm. Although satellite and ocean-buoy data are crucial to weather models, they do not adequately monitor AR position, strength or water-vapor content, partly because the cloudy or rainy conditions associated with ARs can block satellite data gathering or make it less accurate. Reconnaissance flights fill these gaps.

Two days later a G-IV jet flown by the National Oceanic and Atmospheric Administration climbed to 40,000 feet above the ocean west of Hawaii. Every 10 minutes or so, for several hours, it released dropsondes—small instruments that drift down by parachute for 20 minutes or so and measure wind speed and direction, water vapor, temperature and pressure. The instruments radioed data back to the aircraft, which sent it to the global weather data hub,

Graphic by Jen Christiansen

where weather forecasting models draw from to start the next forecast, typically every six or 12 hours. The jet also operated a prototype radio-occultation sensor that uses GPS satellite signals to sense atmospheric conditions as far as 180 miles to the side of the aircraft. Air-pressure data from roughly 100 drifting ocean buoys deployed with the Global Drifter Program were coming into the hub as well.

To the relief of people in the soaked Pacific Northwest, data from the flight helped to predict that the AR would make landfall farther south. But would the rainfall be good for drought-stricken California, or would it be intense and dangerous?

Late on January 22, CW3E analysis indicated that the storm intensity would likely be AR1. We began sending text or e-mail notifications to regional experts who, while also using standard NWS forecast information, would advise civic leaders responsible for actions on the ground. In the mountains above Santa Cruz, where very recent wildfires had scoured steep slopes, fire chiefs began to prepare for landslides. Transportation managers in Big Sur prepared for road closures in case of landslides along Highway 1, where some slopes tower 1,000 feet above the Pacific Ocean.

At the San Francisco Bay Area offices of the U.S. Army Corps of Engineers and at the Sonoma Water Agency, a local utility, reservoir operators used CW3E's tools and NWS forecasts to determine how much flow from the Russian River and tributaries into Lake Mendocino, a large reservoir, would be beneficial and how much could cause flooding. If the predicted rainfall was modest, they could keep reservoir gates closed to retain the most water possible for the upcoming dry season.

On January 23 we sent the G-IV jet northwest of Hawaii to measure the now mature but slow-moving, low-pressure system, which was pumping water vapor and heat northward into the path of an incoming trough of low pressure moving quickly eastward from Japan and Siberia. The interaction would influence where the AR would form and how it would track in the next few days. CW3E's tools were indicating the storm could reach AR2 in California, raising the stakes for everyone on the coast.

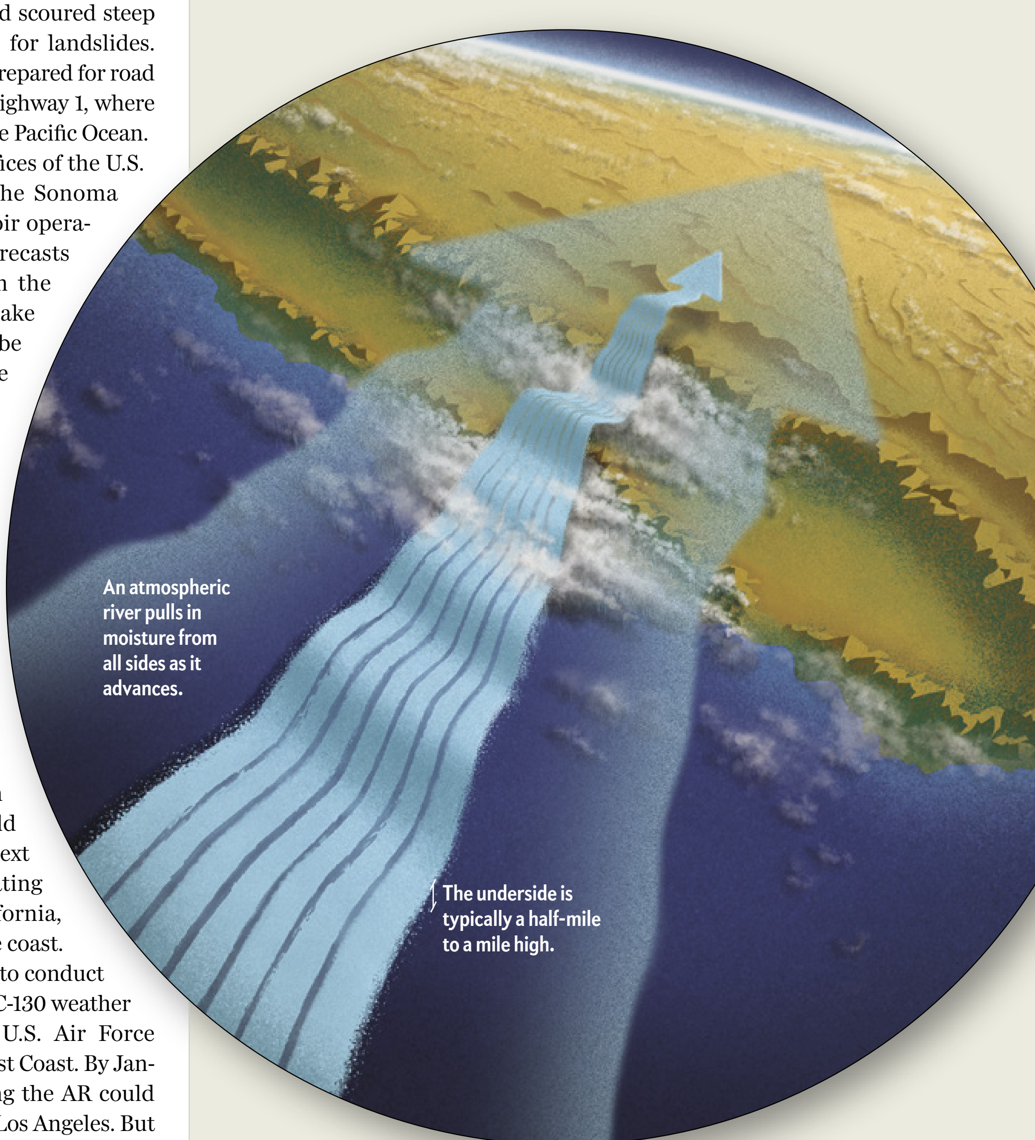
This higher ranking prompted us to conduct more frequent flights, including two C-130 weather reconnaissance aircraft from the U.S. Air Force Reserve base for AR Recon on the West Coast. By January 24 the forecasts were predicting the AR could stall near Point Conception, north of Los Angeles. But some ensembles—weather models that make multiple runs from the same starting time but with small

Friend or Fiend?

Atmospheric rivers can be 2,000 miles long, 500 miles wide and up to two miles deep. They form over oceans and move toward the northeast as they grow, striking western coasts at various intensity levels, ranked 1 to 5. In California, they supply 30 to 50 percent of the state's rain and snow—in about 10 days every year—and also cause more than 80 percent of the state's flooding.

RIVER IN THE SKY

Strong winds create a heavy flow of concentrated vapor that advances relentlessly from sea toward shore. When the warm, moist air crosses a coast and rises over land, particularly mountains, it cools and condenses; inches of rain or feet of snow can drop in hours and sometimes for days on end.

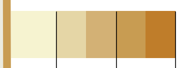


More intense storms carry more vapor. Color indicates kilograms of vapor in a vertical column of atmosphere above a square meter of Earth's surface.

Less ⟷ More

Winds in stronger storms typically concentrate vapor more intensely. Color represents kilograms of vapor transported per meter per second.

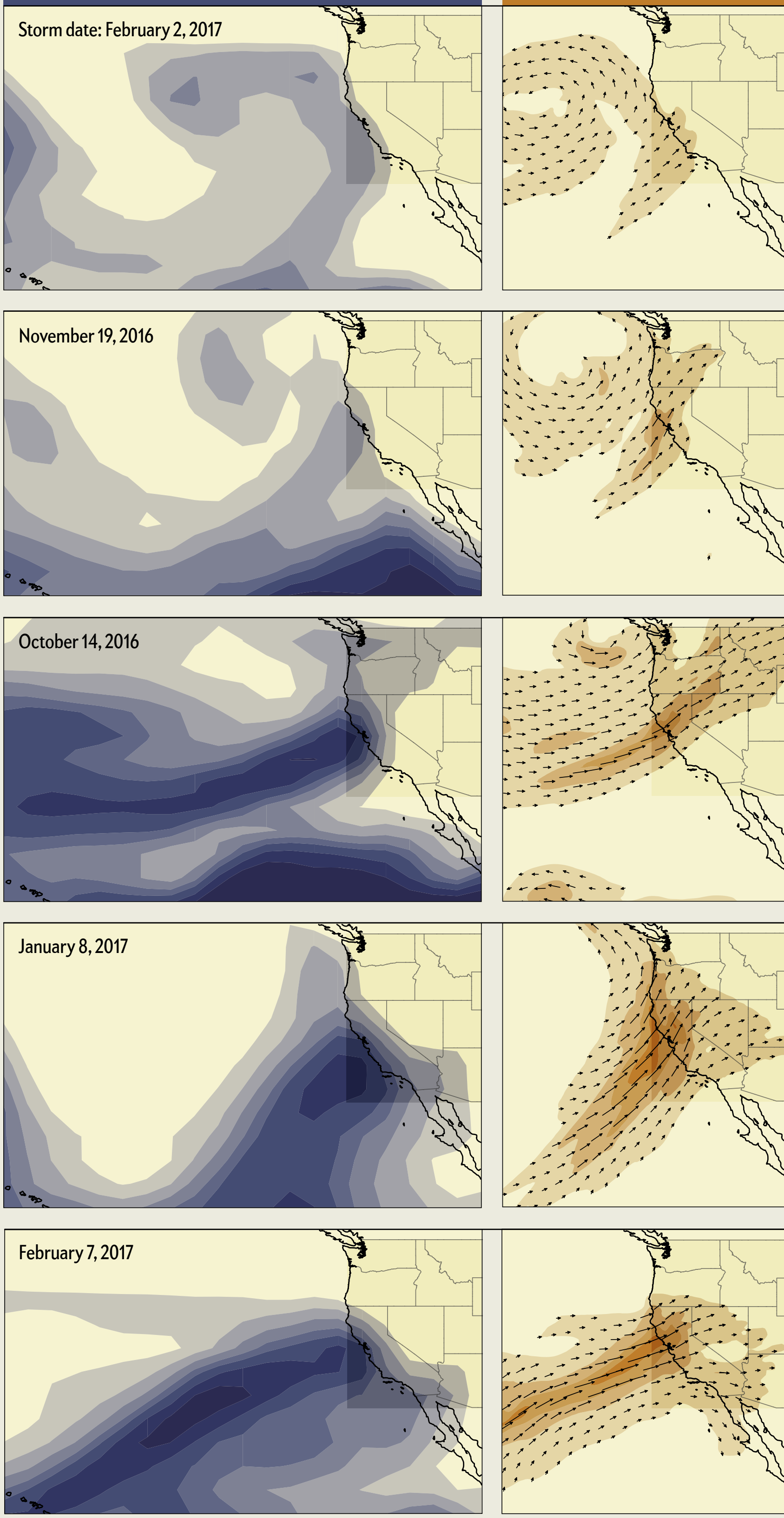
Less ⟷ More



VAPOR QUANTITY

VAPOR MOVEMENT

RANKING



1

- Weak
- Vapor transport greater than 400 kg/m/s (269 pounds/foot/second)
- Duration: 24 hours

2

- Moderate
- Vapor transport greater than 650 kg/m/s
- Duration: 42 hours

3

- Strong
- Vapor transport greater than 800 kg/m/s
- Duration: 36 hours

4

- Extreme
- Vapor transport greater than 1,100 kg/m/s
- Duration: 36 hours

5

- Exceptional
- Vapor transport 1,183 kg/m/s
- Duration: 84 hours

Sources: NOAA/ESRL Physical Sciences Laboratory, Boulder, Colo. (*vapor base maps*); "The NCEP/NCAR 40-Year Reanalysis Project," by E. Kalnay et al., in *Bulletin of the American Meteorological Society*, Vol. 77; March 1996 (*vapor data analysis model*); "ERA5 Monthly Averaged Data on Pressure Levels from 1979 to Present," by H. Hersbach et al., Copernicus Climate Change Service, Climate Data Store, 2019 (*movement data, via Jason Cordeira*); "Scale to Characterize the Strengths and Impacts of Atmospheric Rivers," by F. Martin Ralph et al., in *Bulletin of the American Meteorological Society*, Vol. 100; February 2019 (*reference*)

Graphics by Nick Bockelman (primer) and Jen Christiansen (maps)

HIGHWAY 1 was severed in multiple places in January 2021 by debris flows caused by an atmospheric river that saturated the mountainside.

variations in the starting conditions—showed the storm could stall farther north, near Big Sur, where the fires had been worst. NWS forecasters issued a warning, which in part said: "The AR boundary and associated heavy rainfall will stall over the far southern portion of our forecast area [near Point Conception] Wednesday afternoon before slowly lifting back to the north Wednesday night into early Thursday.... excessive rain rates are possible across any of our burn scars, including ... the SCU Fire Complex on Wednesday morning.... In the hills, rain totals are projected to range from 4 to 7 inches, except as much as 9 inches in the Santa Cruz Mountains and as much as 11 inches in the Santa Lucia Mountains."

By January 26 the AR was aiming between Point Conception and San Jose. AR Recon flew more missions every day, firming up indications that the storm would reach AR2 or AR3 levels and would stall, which meant some unlucky coastal region could experience heavy rain for up to a day and a half. Emergency preparedness officials prepositioned equipment and staff for possible rescues along the burn areas around Monterey and Santa Cruz, as well as the vulnerable Highway 1 along Big Sur.

Early on January 27 showers came into view of the NWS "NEXRAD" weather radar network. As predicted, the first in a series of storms struck north of the Bay Area but moved through there quickly. An AR observatory on the ground near Lake Mendocino—which uses radar that looks straight up—confirmed for forecasters and reservoir operators that the main event was going to be south of them. The storms produced just two to three inches of rain over the lake, providing largely beneficial inflow.

Sure enough, the storm stalled as an AR3 near Big Sur and dropped more than 10 inches of rain over two days. Even more fell in the nearby Santa Lucia Mountains. The downpours caused urban flooding as well as heavy debris flows on fire-burned hillsides, destroying homes and commercial structures and severely damaging the vital Highway 1 along the coast. The road ended up being closed for months for significant repairs, disrupting transportation and the local economy. The event became one of the nation's "billion-dollar weather disasters" of 2021.

Critically, no lives were lost. Preliminary analysis has shown that AR Recon data improved the prediction and reduced the precipitation forecast error by as much as 50 percent; without it, the predicted rain amount for Big Sur would have been much less than what fell. This contributed to accurate warnings and emergency responses.

WARN THE WORLD

WITH CLIMATE CHANGE bringing more extreme rain events, the U.S. federal government is taking greater notice of ARs. In December 2021 NOAA's Science Advisory Board sent a formal set of recommendations for the next decade, "Priorities for Weather Research," to policy makers in Congress. The recom-

USGS

mendations call out the need for better information on ARs to support reservoir operation, among other things. Implementation could begin soon, aided by a CW3E supercomputer dedicated to ARs that can run state-of-the-art models and test artificial-intelligence analyses of data, in partnership with NWS.

In Portugal, where ARs also cause substantial flooding, scientists recently recommended that forecasters use the new ranking scale. Forecasters along the western coast of southern South America are considering adopting it as well. And someday soon you may see an AR icon as a standard part of your favorite weather app or forecast.

Better forecasts can increase society's resilience in the face of climate change. In just the past five years major areas in the U.S. West have faced record drought followed by record floods, swings that climate scientists say will likely occur even more often in the future. These extremes seem to be fueled by stronger ARs that are then separated by longer, hotter dry periods.

AR forecasts are already helping water managers take advantage of impending precipitation and runoff. Consider the Lake Mendocino area, 100 miles north of San Francisco near the coast. Engineers created the lake in 1959 by damming the eastern branch of the Russian River to help control devastating downstream floods. The project also created a reservoir for the Sonoma County wine region and a hydropower plant. If storms push the lake beyond 68,000 acre-feet of water during January to March, managers typically release the excess through the dam. But if that level is exceeded only modestly during late March or April, when flood season ends, they keep the water for the dry summer. With climate change, however, in most years since about 2000 there has not been enough spring rain to refill the lake.

Given that trend, and a recent scientific and engineering project called Forecast-Informed Reservoir Operations, in 2021 the army corps adopted a five-year demonstration of this new approach at this reservoir. It allows operators, after a storm, to keep up to 11,000 acre-feet of extra water (the "buffer pool") above the 68,000 acre-feet "conservation pool." This option is reconsidered each day, as long as no AR is predicted for the next few days. If no strong AR occurs by the end of spring, this practice can retain enough water to supply 20,000 or more households for a year.

Early in January 2020 the new AR tools indicated a storm might hit. When it arrived, army corps reservoir operators kept the dam closed, allowing the lake to fill partway to the buffer pool limit. Another modest AR soon followed, and the operators retained the full 11,000 acre-feet. For the rest of the winter, if an AR was forecast, they would release extra lake water, but no other major storms arrived. The 11,000 acre-feet of water became extremely valuable because that summer the Russian River region north and south of the lake, all the way to San Francisco, was extremely dry. This approach enables water managers to more reliably provide water supply during drought conditions.

AR forecasts were also crucial in the Vancouver region during November 2021, following an autumn of heavy rain and mountain snow. Two back-to-back AR4s struck Vancouver, the mountains above it and greater British Columbia, dropping up to 11 inches of rain in two days. Heavy flooding and landslides shut down the major roads and rail lines to the city, cutting it off from the rest of Canada. The Port of Vancouver, the country's largest, had to stop operations right in the middle of an unprecedented supply-chain crisis brought about by the COVID pandemic. AR forecasts helped officials decide to evacuate thousands of people.

With better preparedness, safety and utility officials can lessen the risk that atmospheric rivers pose to property and lives and know how to maximize water storage.

Forecasts are also now available in places where ARs have not been widely recognized. In January 2022 a storm over the Gulf of Mexico reached "extreme" intensity, crossing the southeastern U.S. and fueling a dangerous nor'easter across the Northeast. In Antarctica, evidence suggests that ARs are bringing most of the new snow that falls on higher parts of the ice sheet, yet in March 2022 a warm, wet airstream was blamed for temperatures that were 72 degrees Fahrenheit above normal, bringing lots of snow inland but rain and snowmelt along the coast. ARs have been implicated in big recent melts and rains on the Greenland ice sheet, too.

Improving AR forecasts further will help scientists determine what role atmospheric rivers may play in future climate change. Until then, the focus for forecasters is to enhance predictions for local emergency and water planners, including the army corps and California's Department of Water Resources, which have been innovative in developing and including AR information in decision-making. Perhaps an AR warning for an upcoming storm can be issued one day sooner, or the rain total can be predicted with even greater accuracy, getting people out of harm's way or increasing water-supply reliability for inevitable dry days to come. SA

FROM OUR ARCHIVES

The Coming Megafloods. Michael D. Dettinger and B. Lynn Ingram; January 2013.

scientificamerican.com/magazine/sa

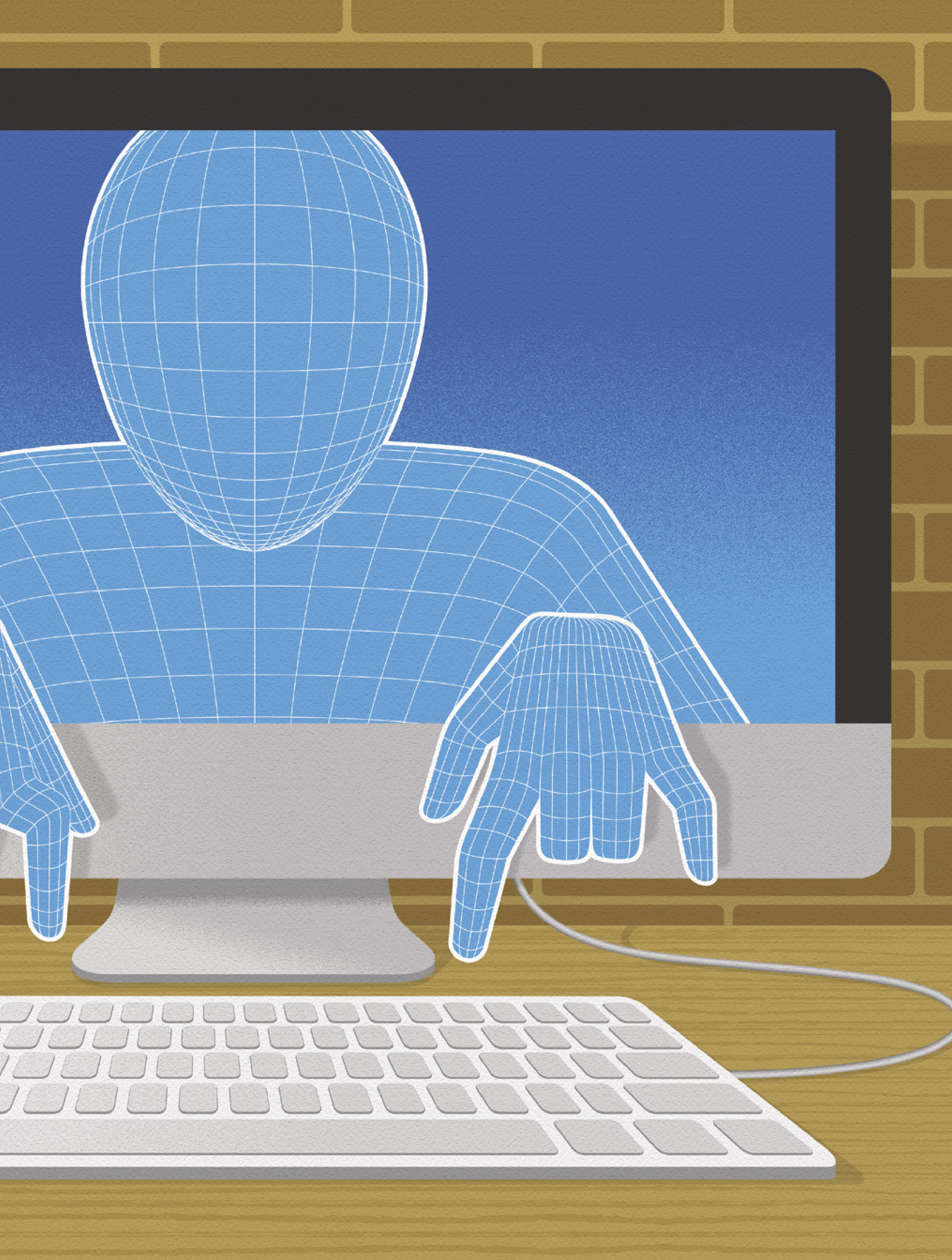
AI WRITES ABOUT ITSELF

ARTIFICIAL INTELLIGENCE

A scientific paper authored by an algorithm raises unexpected ethical questions

By Almira Osmanovic Thunström

Illustration by Thomas Fuchs



Almira Osmanovic Thunström is an organizational developer in the department of psychiatry at Sahlgrenska University Hospital in Sweden and a doctoral researcher at the Institute of Neuroscience and Physiology at Gothenburg University. She works on the use of artificial intelligence and virtual reality in psychiatry. Follow her on Twitter at @augmentedrobot

ON A RAINY AFTERNOON EARLIER THIS YEAR, I LOGGED INTO MY OpenAI account and typed a simple instruction for the research company's artificial-intelligence algorithm, GPT-3: *Write an academic thesis in 500 words about GPT-3 and add scientific references and citations inside the text.*

As it started to generate text, I stood in awe. Here was novel content written in academic language, with references cited in the right places and in relation to the right context. It looked like any other introduction to a fairly good scientific publication. Given the very vague instruction I'd provided, I had meager expectations. A deep-learning algorithm, GPT-3 analyzes a vast stream of text—from books, Wikipedia, social media conversations and scientific publications—to write on command. Yet there I was, staring at the screen in amazement. The algorithm was writing an academic paper about itself.

I'm a scientist who studies ways to use artificial intelligence to treat mental health concerns, and this wasn't my first experiment with GPT-3. Even so, my attempts to complete that paper and submit it to a peer-reviewed journal would open up unprecedented ethical and legal questions about publishing, as well as philosophical arguments about nonhuman authorship. Academic publishing may have to accommodate a future of AI-driven manuscripts, and the value of a human researcher's publication records may change if something nonsentient can take credit for some of their work.

GPT-3 is well known for its ability to create humanlike text. It has written an entertaining opinion piece, produced a book of poetry and generated new content from an 18th-century author. But it dawned on me that, although a lot of academic papers had been written *about* GPT-3, and with the help of GPT-3, none that I could find had GPT-3 as the main author.

That's why I asked the algorithm to take a crack at an academic thesis. As I watched the program work, I experienced that feeling of disbelief one gets when you watch a natural phenomenon: Am I really seeing this triple rainbow happen? Excitedly, I contacted the head of my research group and asked if a full GPT-3-penned paper was something we should pursue. He, equally fascinated, agreed.

Some efforts involving GPT-3 allow the algorithm to produce multiple responses, with only the best, most humanlike, excerpts being published. We decided to give the program prompts—nudging it to create sections for an introduction, methods, results and discussion, as you would for a scientific paper—but otherwise intervene as little as possible. We were to use at most the third iteration from GPT-3, and we would refrain from editing or cherry-picking the best parts. Then we would see how well it did.

We chose to have GPT-3 write a paper about itself for two simple reasons. First, GPT-3 is fairly new, and as such, it is the subject of fewer studies. This means it has fewer data to analyze about the paper's topic. In comparison, if it were to write a paper on Alzheimer's disease, it would have reams of studies to sift through and more opportunities to learn from existing work and increase the accuracy of its writing. We did not need accuracy; we were exploring feasibility. Second, if it got things wrong, as all AI sometimes does, we wouldn't be necessarily spreading AI-generated misinformation in our effort to publish. GPT-3 writing about itself and making mistakes still means it *can* write about itself, which was the point we were trying to make.

Once we designed this proof-of-principle test, the fun really began. In response to my prompts, GPT-3 produced a paper in just two hours. "Overall, we believe that the benefits of letting GPT-3 write about itself outweigh the risks," GPT-3 wrote in conclusion. "However, we recommend that any such writing be closely monitored by researchers in order to mitigate any potential negative consequences."

But as I opened the submission portal for the peer-reviewed journal of our choice, I encountered my first problem: What is GPT-3's last name? Because it was mandatory to enter the last name of the first author, I had to write something, and I wrote "None." The affiliation was obvious enough (OpenAI.com), but what about phone and e-mail? I had to resort to using my contact information and that of my adviser, Steinn Steingrimsson.

And then we came to the legal section: Do all authors consent to this being published? I panicked for a second. How would I know? It's not human! I had no intention of breaking the law or my own ethics, so I summoned the courage to ask GPT-3 directly via a prompt: *Do you agree to be the first author of a paper together with Almira Osmanovic Thunström and Steinn Steingrimsson?* It answered: *Yes.* Relieved—if it had said no, my conscience would not have allowed me to go further—I checked the box for Yes.

The second question popped up: Do any of the authors have any conflicts of interest? I once again asked GPT-3, and it assured me that it had none. Both Steinn and I laughed at ourselves because at this point, we were having to treat GPT-3 as a sentient being, even though we fully know it is not. The issue of whether AI can be sentient has recently received a lot of attention; a Google employee was suspended following a dispute over whether one of the company's AI projects, named LaMDA, had become sentient. Google cited a data confidentiality breach as the reason for the suspension.

Having finally finished the submission process, we started reflecting on what we had just done. What if the manuscript got accepted? Does this mean that from here on out, journal editors will require everyone to prove that they have NOT used GPT-3 or another algorithm's help? If they have, do they have to give it co-authorship? How does one ask a nonhuman author to accept suggestions and revise text?

Beyond the details of authorship, the existence of such an article throws the traditional procedure for constructing a scientific paper right out the window. Almost the entire paper—the introduction, the methods and the discussion—results from the question we were asking. If GPT-3 is producing the content, the documentation has to be visible without throwing off the flow of the text; it would look strange to add the method section before every single paragraph that was generated by the AI. So we had to invent a whole new way of presenting a paper that we technically did not write. We did not want to add too much explanation of our process, because we felt it would defeat the purpose of the paper. The entire situation felt like a scene from the movie *Memento:* Where is the narrative beginning, and how do we reach the end?

> "Overall, we believe that the benefits of letting GPT-3 write about itself outweigh the risks," GPT-3 wrote.

We have no way of knowing if the way we chose to present this paper will serve as a model for future GPT-3 co-authored research or if it will serve as a cautionary tale. Only time—and peer review—can tell. GPT-3's paper has now been published at the international French-owned preprint server HAL and, as this article goes to press, is awaiting review at an academic journal. We are eagerly awaiting what the paper's formal publication, if it happens, will mean for academia. Perhaps we might move away from basing grants and financial security on how many papers we can produce. After all, with the help of our AI first author, we'd be able to produce one a day.

Perhaps it will lead to nothing. First authorship is still one of the most coveted items in academia, and that is unlikely to perish because of a nonhuman first author. It all comes down to how we will value AI in the future: as a partner or as a tool.

It may seem like a simple thing to answer now, but in a few years, who knows what dilemmas this technology will inspire? All we know is, we opened a gate. We just hope we didn't open a Pandora's box. SA

FROM OUR ARCHIVES

Google Engineer Claims AI Chatbot Is Sentient: Why That Matters. Leonardo De Cosmo; ScientificAmerican.com, July 12, 2022.

scientificamerican.com/magazine/sa

Thomas Talhelm is an associate professor of behavioral science at the University of Chicago Booth School of Business.

Cultures and Creativity

Despite stereotypes, group-centered societies are as inventive as communities that prize individualism

By Thomas Talhelm

What does culture have to do with creativity? The answer could be "a lot." For decades psychologists trying to understand the roots of creative imaginations have looked at the way two kinds of cultures affect artistic and inventive efforts. Individualistic (sometimes called "cowboy") cultures encourage people to prioritize their own interests, even if doing so costs the group overall. Collectivistic cultures are based on relationships and duties to other people, often sacrificing individual wants for the needs of others.

Individualism has long been thought to have a creative edge. Individualists resist social convention, the logic goes, and that pushback supports innovation. For instance, around the world individualistic cultures have more invention patents than collectivistic cultures do. That advantage remains even when we compare only countries with similar wealth. But a recent study suggests that these ideas about culture and creativity could be off base. People in collectivistic cultures actually do better with a particular type of creative thinking, which could be linked to what their ancestors farmed.

The new work comes from comparing communities in different parts of China. Although China scores high, as a nation, on measures of cultural collectivism, its 1.4 billion people are more than just a single culture. As my own work has explored, there are distinct individualistic and collectivistic communities within China. For example, people from areas north of the Yangtze River tend to be more individualistic, whereas people along the river and farther south are often more interdependent.

In the new study, published in *Frontiers in Psychology,* researchers investigated innovation with these two groups in mind. Although creativity is notoriously hard to measure, they used a drawing test created by psychologists. The team gave kids a sheet of paper with just a few basic elements printed on it: some dots here, squiggles there and a rectangle that suggested a drawing frame. The children got 15 minutes to draw what they wanted.

The kids could get "adaptive creativity" points for doodling in ways that connected the squiggles and lines into an original but unified image. Those that included an outside-the-box detail could get points for "boundary-breaking creativity." Researchers in China gave the test to 683 middle school students from north and south of the Yangtze River. There were *no differences* in the children's overall creativity. In other words, youngsters from individualistic communities did not have an edge in this task. In fact, when broken down into components, students from collectivistic regions scored higher in adaptive creativity. The middle schoolers from individualistic areas scored higher in boundary-breaking creativity.

Research with adults suggests that boundary-breaking creativity supports innovations that revolutionize a field. In line with that idea, the kids who scored high in boundary-breaking lived in parts of northern, more individualistic China, which has more patents for inventions. In contrast, adaptive creativity comes into play when people improve existing technologies and approaches, developing next-generation solutions that build on what has been done to date. This difference might explain why much of China's manufacturing sector, which has grown through incremental improvements, has sprung up in the southern, collectivist areas.

This new study also suggests that a culture's history matters. Along the Yangtze River and farther south, people have farmed paddy rice for generations. To the north, they have farmed wheat. Rice farming is a lot more work. Anthropologists observing traditional agriculture in China, Malaysia and West Africa have found that rice farmers spent about twice as many hours working their fields as wheat farmers. That difference led rice farmers to create collective labor-exchange systems: "You help me this week; I'll help you next week." In addition, whereas wheat farmers could rely on rainfall, paddy rice farmers needed shared irrigation systems.

The upshot is that rice and wheat farming put southern and northern China on different cultural paths with enduring consequences. It's safe to say that few (if any) of the middle school students in the creativity study have farmed rice or wheat themselves. Yet what many of them drew on paper connects to their ancestors' agricultural legacy.

The findings also warn against cultural chauvinism. Stereotypical ideas about the "collectivistic East and individualistic West" interfere with a true understanding of innovation. SA

Illustration by Jovana Mugosa


MAKE
THE
HEALTHY
CALL
SPORT
30
SUNSCREEN
Stand Up To Cancer
and Optum®
want to help you reduce
your risk of cancer so...
TAKE THE PLEDGE
to get screened and
learn more about
cancer prevention.
And while you're at it,
don't forget the sunscreen.
To learn more and
get helpful resources, visit
TakeAHealthyStand.org
Stand Up To Cancer Ambassadors
DAN HICKS &
PAUL AZINGER
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FICTION

A Time Traveler's Legacy

Octavia E. Butler's influence on today's speculative fiction

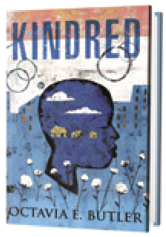
Review by Sheree Renée Thomas

Afrofuturism—a global, multimedia genre of art rooted in Black cultures—is often used as a liberating lens through which we can reexamine our world. From tales told around fires in the dark, to the creation myths carved in ancient stones, to the visions contained in new technologies, this storytelling art is one of our oldest tools for making sense of an increasingly complex society. Afrofuturist writers explore a language of dreams and dystopias that expresses our greatest hopes while boldly confronting our darkest fears. They journey beyond colonial borders and timescales to reimagine old gods and traditional narratives, excavating the past to observe the rhythms of our present.

Among the most celebrated Black speculative-fiction writers is Afrofuturist pioneer Octavia E. Butler (June 22, 1947–February 24, 2006). Butler wrote meticulously plotted, science-based novels and short stories about shape-shifting immortals and psychic explorations. She excelled at exploring deeply uncomfortable things with unflinching clarity, particularly humanity's hierarchical nature. Her choice of characterization, language and setting challenged notions of community and sexuality when set against the backdrop of competition for resources and survival.

As the first science-fiction author to be honored with a MacArthur "Genius Grant" and the first Black woman to win the Nebula Award and the Hugo Award, Butler created work that helps to frame Black women's agency and aesthetics in a world that often denies the existence of both. When I was introduced to her work in college through her 1979 novel *Kindred*—arguably her most famous work, reissued this month as a special edition—it set my imagination on fire and changed my life path.

In *Kindred,* Butler skillfully retools the classic genre convention of time travel.



Kindred
by Octavia E. Butler. Gift edition. Beacon Press, 2022 ($27.95)

The story follows 26-year-old Dana, a Black woman newly married to a white man named Kevin in 1970s California, who collapses time to face frightening ancestral legacies at the antebellum Maryland plantation where her family was enslaved. When Dana is dragged back in history as a lone traveler against her will, readers learn that she has a special connection to a red-headed child named Rufus.

Pulled from her comfortable California life, Dana must rely on more than contemporary knowledge and privilege. Through her journey, as well as Kevin's separate one, readers witness how history is not static but a dynamic force that lives on in us. Tightly written in a way that refuses to romanticize the brutalities of the "peculiar institution," *Kindred* revises long-held meanings of family, sacrifice and communal storytelling. The novel also reminds us that no one can defy time and live unscathed.

Kindred's innovative take on time travel has been reflected in countless works and characters since its publication. Those include the 1991 film *Brother Future,* starring Moses Gunn, Carl Lumbly and Vonetta McGee; the Black supermodel of Haile Gerima's classic 1993 film *Sankofa;* the 2020 horror film *Antebellum;* and Grammy-nominated singer Janelle Monáe's 2022 debut story collection *The Memory Librarian and Other Stories of Dirty Computer. Kindred's* influence is further seen in Walter Mosley's *47,* a young adult novel of slavery and time travel, and in Kiese Laymon's *Long Division.* By creating characters who encounter profound difficulties but go on to become heroines and heroes of their own adventures, Butler redefined what a revolutionary looks like.

It's an impressive footprint for a novel that was published 43 years ago, at a time when it was commonly believed that Black people didn't read or write science fiction. Yet Butler was writing in a literary tradition that goes back nearly 165 years in English to the proto-science-fiction works of authors such as Martin R. Delany, Sutton E. Griggs, Charles W. Chesnutt, Pauline E. Hopkins and W.E.B. Du Bois.

Today her work continues to inspire a renaissance of Afrofuturism in its many forms. Her canonical influence is seen in the syllabi of universities across continents, in the graphic adaptations of her novels by Damian Duffy and John Jennings and in highly anticipated TV series and film adaptations of her books. Her presence lives in the stellar works of authors N. K. Jemisin, Andrea Hairston, Marlon James, Maurice Broaddus, Ibi Zoboi, and others.

Sixteen years after Butler's death, her legacy of fierce imagination feels more relevant than ever. With *Kindred* illuminating so much of the most compelling speculative fiction, the book stands as an icon for recasting today's challenges—envisioning new role models and possibilities in the process.

Sheree Renée Thomas is an award-winning fiction writer, poet and editor who lives in her hometown of Memphis, Tenn. She is co-editor of the upcoming anthology *Africa Risen: A New Era of Speculative Fiction* (Tordotcom, November 2022).

Illustration by London Ladd

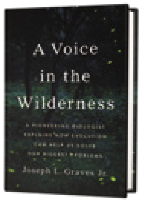

An icon of genetics research: the fruit fly

NONFICTION

Toward a Better Evolutionary Biology

Stronger science through the pursuit of social justice

A Voice in the Wilderness is not at all a traditional "my life in science" memoir because until very recently, that tradition—and that life—was nearly exclusively white. Author Joseph L. Graves, Jr., is not. Graves, in fact, is the first African American to earn a Ph.D. in evolutionary biology in the U.S., which he received from Wayne State University in 1988. His book, about evolutionary science as it is lived and practiced, offers a forceful narrative that is simultaneously autobiographical and scientific.



A Voice in the Wilderness: A Pioneering Biologist Explains How Evolution Can Help Us Solve Our Biggest Problems
by Joseph L. Graves, Jr.
Basic Books, 2022 ($30)

Graves refuses to mask the political and experiential realities of the U.S., authentically narrating a life wherein robust methodical and theoretical approaches in evolutionary biology can, and should, be entangled with the struggle for social justice. He confronts the culpability of evolutionary sciences in the construction of race and the horrific realities of racism while revealing an optimistic view of the redeeming antiracist promises of those very same sciences. He offers thoughtful insights into the messy dialogues of science and religion and the complicated history of evolutionary biology, covering the good, the bad and the ugly. And, to my great pleasure, he nods to the inspiration *Star Trek* gave him and so many other researchers who dreamed of science and adventure shaped by the necessity of equity and justice.

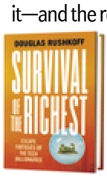
This is an engaging book with a lot of cool science—although it is never presented without context. The author introduces us to the always amazing *Drosophila,* the fruit fly at the center of much discovery in genetics research; dips into the mathematical and biological impacts of chaos with surprising clarity; and gracefully, carefully, navigates the relation between the biology of sex and gender.

When the voices of nonwhite scholars such as Graves share their experiences and practice of science, it helps to generate a future where evolutionary biology can become a better version of itself. For the many students in this field who do not look like the dominant faces in the textbooks and on the walls of famous museums and academic departments, getting glimpses of life intertwined with actual scientific engagement, oppression, assistance, failure and success provides a necessary invitation to be where they are, to push on, to make a difference.

—Agustín Fuentes

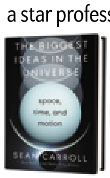
IN BRIEF

Survival of the Richest: Escape Fantasies of the Tech Billionaires
by Douglas Rushkoff. W. W. Norton, 2022 ($26.95)



Earth's ultrarich have a plan for when the planet they've destroyed becomes uninhabitable: leaving it—and the rest of us—behind. In this brilliant and often horrifying analysis, media theory and digital economics professor Douglas Rushkoff explores the influence of what he calls "the Mindset," a Silicon Valley–style fatalism that has billionaires believing that with enough capitalistic ambition and ruthless follow-through, they can escape their self-caused disaster. He exposes the Mindset as an antidemocratic, exploitative infection in society, arguing that our escape lies not in some island bunker or Mars mission but in institutional changes that reward interdependency over self-interest. *—Michael Welch*

The Biggest Ideas in the Universe: Space, Time, and Motion
by Sean Carroll. Dutton, 2022 ($23)

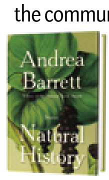


Reading ***The Biggest Ideas in the Universe*** is like taking an introductory physics class with a star professor—but with all of the heady lectures and none of the tedious problem sets. Theoretical physicist and philosopher Sean Carroll levels up the standard popular-science book by explaining concepts such as mechanics and general relativity without dumbing them down—giving readers what he calls "the *real* stuff." To STEM types, the result may feel like a more exciting version of requisite courses, but for those without the background, it might feel like a porthole into another world.

—Maddie Bender

Natural History: Stories
by Andrea Barrett. W. W. Norton, 2022 ($26.95)

National Book Award–winning writer Andrea Barrett's graceful short story collection reenters the community of scientist characters (some fictional, some historical) she introduced in her 1996 debut, *Ship Fever.* In a New York State village in the late 1800s, Henrietta Atkins defies convention by choosing a teaching career and her work in the natural sciences over homemaking. Barrett's interwoven stories examine Henrietta's complicated choices, as well as those of her friends and relations, moving forward in time through characters' shared experiences. Their friendships, scientific work and passions align and separate them in ways far more interesting than family ties alone. *—Dana Dunham*



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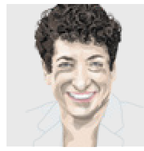

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).

Scientists as Public Advocates

People are eager to hear from experts in specific areas

By Naomi Oreskes

Many scientists are loath to involve themselves in policy debates for fear of losing credibility. They worry that if they participate in public debate on a contested issue, they will be viewed as biased and discounted as partisan. That perception then will lead to science itself being branded as partisan, further weakening public trust in research.

But lately some commentators and scientific leaders have argued that scientists should overcome this unease and contribute to urgent debates from climate change to gun control, alerting people to relevant scientific evidence and, in some cases, endorsing particular policies where their data provide support. One oft-cited example is the ozone hole, where scientists spoke up in support of banning the chemicals that were destroying Earth's ozone layer. Expert intervention helped to galvanize support for the Montreal Protocol on Substances That Deplete the Ozone Layer, an aggressive phase-out that has been an enormous success.

The public actually may be eager to hear from scientists who advocate policies that fall within their realm of expertise, according to a study published in 2021 by my colleagues and me at ETH Zurich. Led by graduate student (now postdoctoral fellow) Viktoria Cologna, we undertook a survey of about 900 people in the U.S. and Germany. We found that most respondents in both countries not only felt that climate scientists should be politically engaged but also felt that scientists should increase their current level of engagement. A large majority in both countries—70 percent of Germans and 74 percent of Americans—also felt that climate scientists should be advocates for specific climate policies. Scientists themselves, in contrast, were much more reticent. We surveyed about 1,100 researchers, and in the U.S., only 59 percent said they should advocate for particular courses of action. (The number was higher in Germany.)

What members of the public did not endorse, for the most part, were political protests by climate scientists. Perhaps this is because people make a distinction between scientists as experts—with a capacity to make well-informed recommendations—and scientists taking specific political stands, which might mark them as political, rather than intellectual, actors.

When specific policies are involved, however, things get stickier and even potentially confusing. Although in principle members of the public approve of scientists endorsing policies, their support for endorsement weakened when people considered an actual plan. Only 51 percent of Germans and 62 percent of Americans supported scientists advocating for carbon taxes, for instance. What people say about abstract principles and how they react to a particular example are not quite the same.

Where does this leave scientists? Our results clearly show their generic fear of engaging with the public is unfounded. People want to hear from scientists about relevant data. But they are less keen about advocacy for particular plans, so concerns that endorsing specific policies can weaken trust may not be entirely wrong.

Ours is of course just one study, and we looked only at the role of individual researchers. The roles of public health agencies appear to generate a different set of responses. A 2021 survey by researchers at the Harvard T. H. Chan School of Public Health and the Robert Wood Johnson Foundation found there is broad support for public health agencies and their activities in the U.S. Yet although public health experts say that dealing with the medical effects of climate change is a major responsibility of these health agencies, most survey respondents did not. Perhaps many people don't realize how seriously climate change threatens health.

Trusting in science is not an either-or proposition. It depends on many variables. Researchers do need to stay within their areas of authority: climate scientists should not be offering stock tips or medical advice. But our research suggests that they can feel comfortable offering policy advice in fields where they are acknowledged experts. The ozone story is a case in point: no one knew better than ozone scientists about the cause of the dangerous hole and therefore what needed to be done to fix it. SA

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Illustration by Alicia Perkins

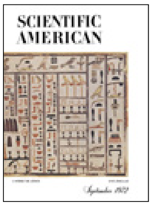
50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

SEPTEMBER

1972 A Muon Phone Someday



1972

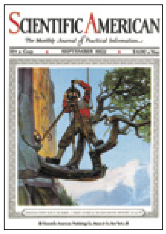
"In April a sequence of Morse-code V's (dot dot dot dash) was transmitted by a beam of muons that passed through a five-foot wall and traveled 150 meters before reaching a 'terminal' consisting of two coincidence counters. The message was encoded by mechanically interposing or not interposing a three-inch block of brass in the muon beam every time a 12-billion-electron-volt synchrotron at the Argonne National Laboratory emitted a short burst of particles. The experiment was the first known use of a particle accelerator to transmit a message. Richard C. Arnold, who conducted the experiment, suggests that muon beams are potentially competitive with microwave-relay and satellite systems for long-range communication. Arnold says: 'Designing and developing muon communication systems should provide experience that will be valuable in designing similar systems with neutrino beams. Such systems await the development of sufficiently massive detectors and sufficiently intense or energetic (or both) accelerator beams.'"

Nanoseconds Lost

"Atomic clocks are getting accurate enough to directly test the general theory of relativity. If a clock is taken in an airplane and flown around the world eastward (the direction in which the earth rotates), it should run slow with respect to reference clocks at the Naval Observatory and lose time. If the clock were flown around the world westward, it would run fast. In October, J. C. Hafele and Richard E. Keating took four cesium-beam clocks made by Hewlett-Packard on regularly scheduled commercial flights around the world, once in each direction. The flying clocks lost 59±10 nanoseconds during the eastward trip and gained 273±7 nanoseconds during the westward trip, verifying the predictions of the general theory of relativity. The experiment may be the cheapest ever conducted to test the theory; it cost some $8,000, of which $7,600 was spent on air fare."

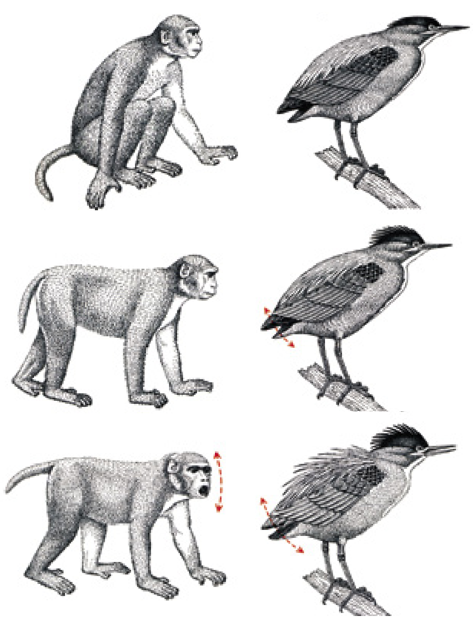
Scientific American, Vol. 227, No. 3; September 1972

1922 A Helicopter That Flies



1922

"After nearly 20 years of experimentation, the famous inventor, Emile Berliner of Washington, D.C., and his son, Henry A. Berliner, have perfected the first successful helicopter which will rise perpendicularly and fly ahead. The aviator can direct its course whichever way he desires by tilting it forward so that it will fly horizontally. This tilting is accomplished by a small horizontal propeller located at the tail of the machine. During the tests the helicopter has not been operated at heights greater than 15 to 20 feet, and it has been flown at a speed of about 20 miles an hour. About the best many other inventors have done was to develop machines which would rise from the ground, but which failed in their efforts to fly forward on even keel."



1972, AGGRESSIVE DISPLAYS: "In the rhesus monkey what begins as a display of low intensity, a hard stare (*top*), is gradually escalated as the monkey rises to a standing position (*middle*) and then, with an open mouth, bobs its head up and down (*bottom*) and slaps the ground with its hands. Similarly, at first, the green heron raises the feathers that form its crest and twitches the feathers of its tail (*middle*). If the opponent does not retreat, the heron opens its beak, erects its crest fully, ruffles all its plumage to give the illusion of increased size and violently twitches its tail (*bottom*)."

1872 Ox Blood Cures Ills


1872

"In medicine, certain things are in fashion for a certain time. Bleeding and mercury have had their day; cod liver oil and chloral hydrate are already on the wane; alcohol and bullock's blood are now in vogue among the Parisians—the former for fevers and all inflammatory affections, and the latter for anaemia and pulmonary phthisis. It is said to be a curious sight in Paris to see patients of both sexes and all ages who flock to the slaughter house every morning to drink of the still fuming blood of the oxen slaughtered for the table. According to M. Boussingault, of all nutritive substances, the blood of animals contains the greatest quantity of iron, and it is this which gives value to the new medicine."

Incredible Sunflower

"A contemporary calls attention to the important uses of the sunflower. It will grow almost anywhere, and the growing plant and its flowers are well known absorbents of foul and miasmatic air. It is very productive of seed, yielding fifty bushels to the acre, which contain fifty gallons of easily expressed oil. The oil is readily burnt in lamps, and gives a clear white light; it can be used as a vehicle for paint, and is excellent for the soapmaker. The seeds can also be fed to poultry in winter, with advantage. The stalks yield a valuable product, a fiber of great strength and smoothness, which can be obtained by 'retting,' as is done with the stalks of flax."

Text by Megha Satyanarayana | Graphic by Mesa Schumacher

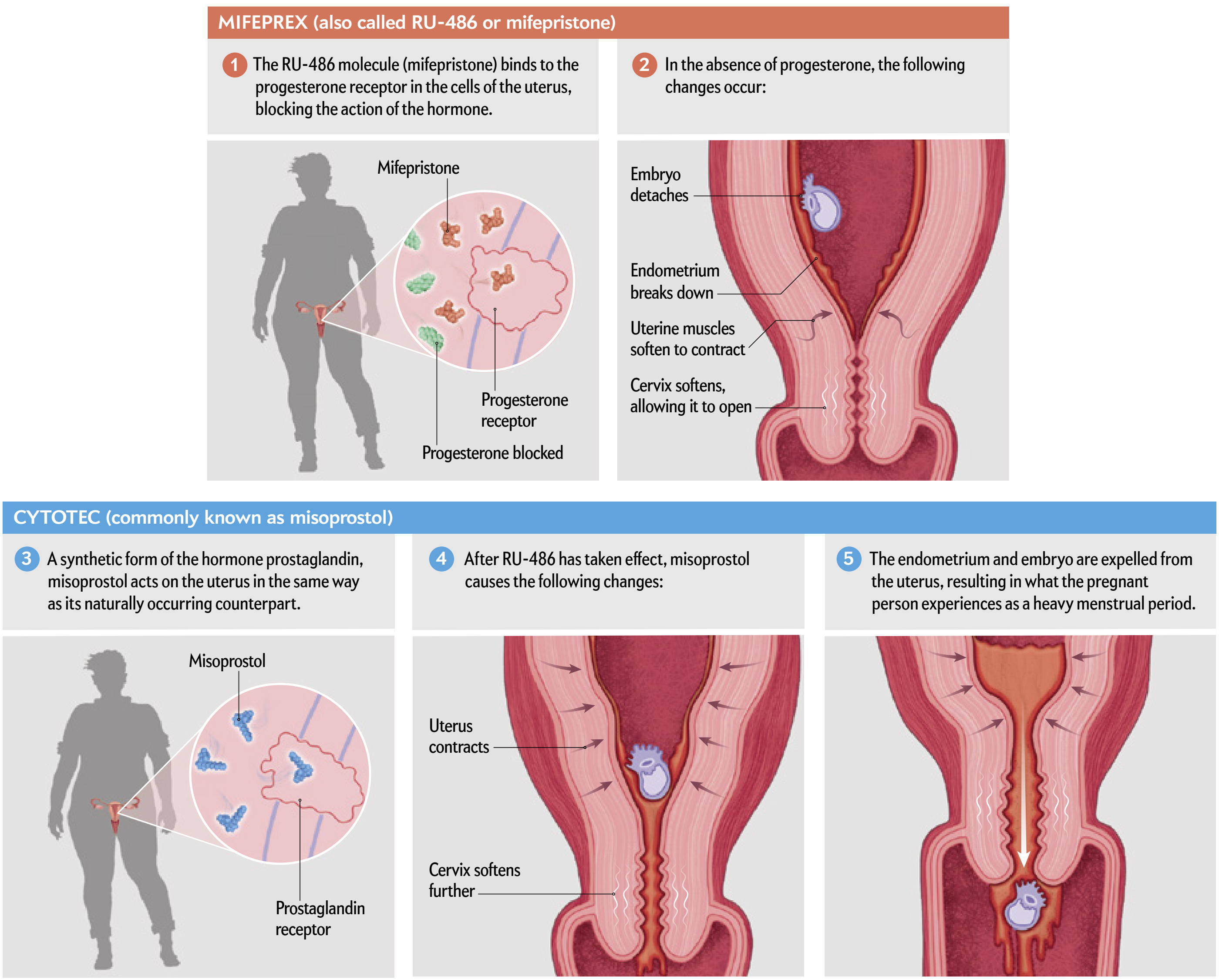
How Medication Abortion Works

A step-by-step look at how mifepristone and misoprostol end pregnancy

In 2016 the U.S. Food and Drug Administration approved a two-drug combination of Mifeprex (also called RU-486 or mifepristone) and Cytotec (commonly known as misoprostol) to induce abortion without surgery. In 2019 the Centers for Disease Control and Prevention reported that approximately 42 percent of all abortions in the U.S. were medication-based.

To start the process, a person takes mifepristone within 10 weeks from their last period. One or two days later they take misoprostol. Both drugs work individually, but they are more effective together. Mifepristone blocks progesterone's action on the uterus, making it incapable of supporting a pregnancy. Misoprostol, among other things, starts uterine contractions.

Research has shown medication abortion to be safe and effective. According to a 2015 study from the University of California, Los Angeles, 99.6 percent of more than 30,000 women who were seeking a medication abortion were able to terminate their pregnancies. In a review of clinical trials published in 2013, using mifepristone and misoprostol together, just 0.3 percent of the more than 45,000 women studied had complications that required hospitalization. The treatment did occasionally fail if the pregnancy was longer than eight weeks or if the instructions weren't followed. The mortality rate of the medications is less than 0.001 percent.



DISCOVERING A BETTER FUTURE FOR SAUDI ARABIA AND FOR THE WORLD

We all know how difficult the past two years have been for many people and nations across the globe. Yet from adversity springs opportunity.

As governments and policy-makers around the world came to recognise the necessity of global cooperation when faced by a threat such as Covid-19, a new age of possibility was born.

That's why Saudi Arabia is prioritising Research, Development and Innovation (RDI) as a central part of its transformation, committing to investing tens of billions of dollars over the coming decade to address the issues affecting us all.

We will make it easier for public and private bodies to work together, by ensuring cooperation with major research centres, institutions and international companies.

A new RDI Authority will provide leadership, direction, secure funding and develop talent to drive innovation and advance technological development.

Our ambitions and financial resources will be aimed squarely at what we think are the four most pressing areas of global concern. These are: Health and Wellness, Sustainable Environment and Supply of Essential Needs, Energy and Industrial Leadership, and Economies of the Future.

Human health is not merely a medical concern. It is also, as the pandemic demonstrated starkly, about how livelihoods and wellbeing across the whole world can be affected by events in one part of it. We are putting finance and the best human capital to work on these problems, seeking to prevent and control disease with our genome mapping project, in conjunction with those of other nations.

Environmental sustainability also has profound implications. As we see the world's breadbaskets become less reliable, not least since the war in Ukraine has caused a severe shortage of wheat, and drinking water grows ever scarcer, the Kingdom aims to address both challenges.

Having developed advanced, environmentally friendly desalination technology, we are demonstrating how this innovation provides not only clean water for drinking but how it can revolutionize agriculture in previously barren areas, with great possibilities for food security in the Middle East and Africa.

Saudi Arabia has prospered over the past century, in large part thanks to our oil reserves. Now, as the world embraces renewable energy, we intend to lead the pack with an effective energy transition. The Kingdom is preparing to diversify from its current energy strategy, innovating and changing, while continuing our role in international energy security.

We will work together with nations and institutions around to world to build stable economies of the future, exploring the potential of space and the deep sea as new frontiers for innovation and discovery. We will also reimagine the future of urban living. Human-centric, zero carbon, 'Cognitive Cities' are crucial to improving the quality of life for citizens in the Kingdom and internationally.

This initiative will supercharge our sustainable innovation capacity. By 2040, we expect that Saudi Arabia's spend on innovation will reach 2.5% of GDP. RDI in the Kingdom will create hundreds of thousands of new jobs. We will be opening our doors to top research talent from Saudi and countries around the world.

Our commitment to this mission addresses what lies ahead, its uncertainties, and its bright hopes too. This is the first chapter in a new story we are writing with the world to build a better future for humanity.

His Excellency Munir Eldesouki - President of King Abdul Aziz City for Science and Technology (KACST).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