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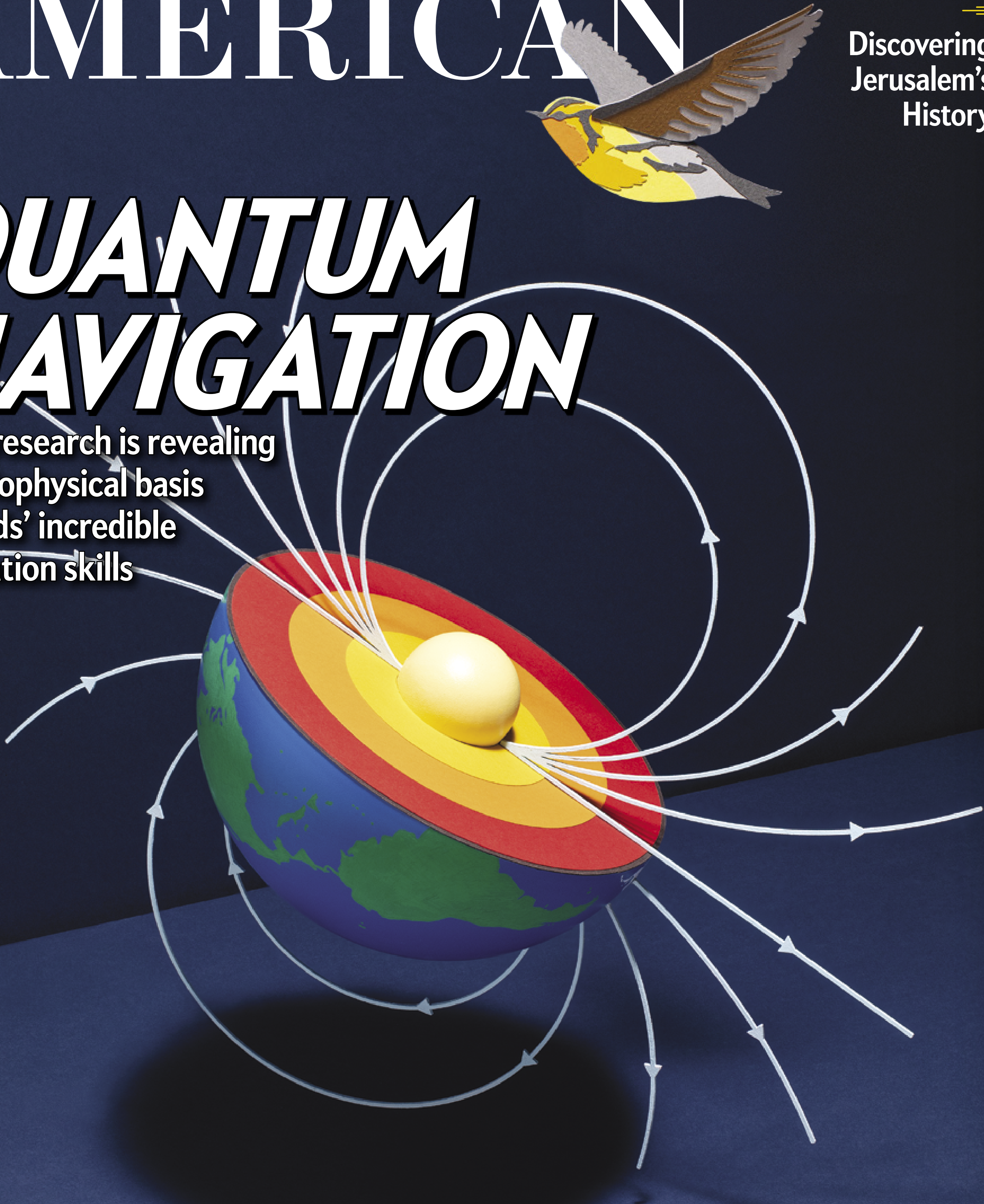
Searching the Sky for Dark Matter

Resurrecting Rivers

Discovering Jerusalem's History



QUANTUM NAVIGATION

New research is revealing the biophysical basis of birds' incredible migration skills

APRIL 2022

VOLUME 326, NUMBER 4

SCIENTIFIC AMERICAN

ON THE COVER
Every year billions of birds travel long distances between their breeding and wintering grounds. Scientists have known for a while that they use the sun and stars to navigate. But birds also use Earth's magnetic field to orient themselves. New research suggests that their magnetic compass relies on quantum physics. **Illustration by Kyle Bean.**

Photograph by Jelle Wagenaar

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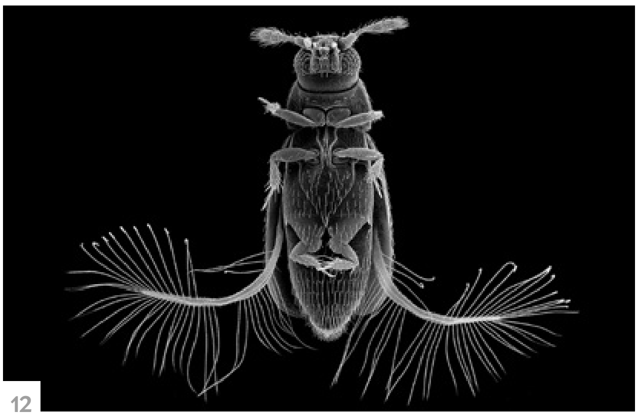
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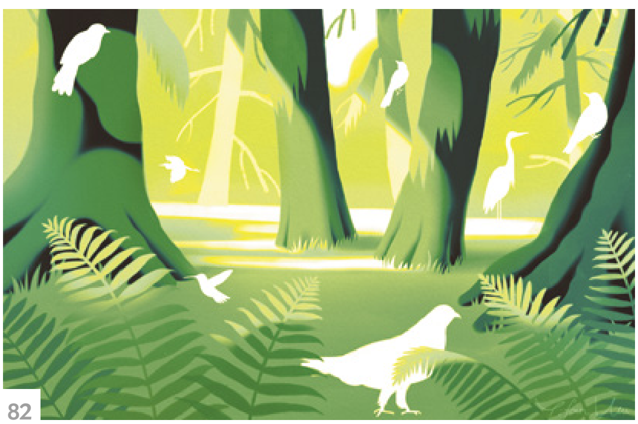
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Laura Helmuth is editor in chief of *Scientific American*. Follow her on Twitter @laurahelmuth

Magnetic Vision

While we sleep this spring, billions of birds will be flying through the night from their wintering grounds to their breeding territories. Bird migration is a mind-bendingly astonishing phenomenon: these tiny creatures fly thousands of kilometers with enough precision to return to the same nesting site year after year. They use three types of compass, guided by the stars, sun and, most mysteriously, Earth's magnetic field. In this issue's cover story on page 26, scientists Peter J. Hore and Henrik Mouritsen explain how some birds are able to "see" Earth's magnetic field using quantum effects in exquisitely photosensitive molecules in their eyes. We hope this article will add to the enjoyment of seeing migratory birds return to your neighborhoods after a long winter.

I've been looking at streams with more appreciation after reading about their "hyporheic zone," the area of streambed extending below the water and to the sides of a waterway. This hidden layer of sand and gravel, where the groundwater and stream mix, is home to small animals and larvae and microbes. As author Erica Gies describes on page 40, it's known as the "liver of the river" because of how it keeps a waterway healthy. People who are restoring drained or dying streams are using new knowledge about the hyporheic zone to bring back thriving habitats.

Looking up from streams and beyond the birds, astronomers are planning ambitious projects to seek the source of dark matter, the invisible stuff in the universe that moves stars and galaxies (*page 58*). Theoretical physicist Chanda Prescod-Weinstein presents the best ideas for how to look for dark matter, some of which could get a boost this year if physicists involved in a once-a-decade planning project endorse dark matter probes as a top scientific priority. (We hope they do.)

The culture of astronomy has been transformed by a wave of women entering the field (including *Scientific American* advisory board member Meg Urry), as writer Ann Finkbeiner observes on page 32. She is admired in science writing circles for inspiring the "Finkbeiner test," a guide to avoiding sexist clichés when talking about women in science. Now she realizes we are in a new era, when women are proudly themselves and determined to make science more welcoming to all.

Biblical archaeology is another field being transformed, albeit fitfully. Researchers using modern analytical methods are trying to add some rigor to excavations in Jerusalem, which have been guided by scripture rather than science. On page 66, author Andrew Lawler shows how religious and international conflicts add to physical constraints (the land is very crumbly) to make this one of the most challenging places in the world to unearth true history.

Modern neuroscience began with Santiago Ramón y Cajal's careful observations of neurons and how they interact. Author Benjamin Ehrlich, on page 50, details how revolutionary Cajal's ideas were and how they changed the way we think about the brain. The painstakingly drawn illustrations are indeed wondrous.

In 1889 *Scientific American* shared some of Thomas Edison's thoughts on sleep. He was against it. But he did appreciate napping—or at least the half-asleep state that led to many of his inspirations. Starting on page 74, you can learn how to follow his advice to extract creativity from a snooze. Writer Bret Stetka tells the tale.

We're introducing a print column this month called Mind Matters (*page 78*), in which experts will share recent interesting insights from social science. Enjoy, and let us know what you think.

Illustration by Nick Higgins


SPECIAL ISSUE : SEX AND GENDER
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SPEAKING IN WHISTLES • WHAT'S WRONG WITH COSMIC INFLATION?
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MISOGYNY'S COLD SHOULDER

In "Women on Ice" [Observatory], Naomi Oreskes describes how she applied to a geologist position at the British Antarctic Survey (BAS) in 1981 and was rejected because she was a woman. I applied to the BAS in 1972, when they were looking for meteorological observers. I received a response similar to Oreskes's. There was no mention of tents, but the letter essentially said, "It is not that we are misogynists, but we do not have facilities for women." Ah, well. I went off and did something else!

Christine Vibert *Jersey, British Isles*

I continue to be angered by the ways women in science are treated. I am reminded of a former student's experience with her male high school guidance counselor: When she told him she intended to study biochemistry at a university and then head to medical school to pursue a career in research, he shrugged and asked, "Wouldn't it just be easier to be a nurse?" Although I teach in the humanities, I will forever champion young women in whatever direction their dreams take them. I heard from my former student several years later: she was preparing to graduate from medical school and to receive a Ph.D. in biochemistry.

Virgil Miller
Madison Area Technical College

"I continue to be angered by the ways women in science are treated."

VIRGIL MILLER
MADISON AREA TECHNICAL COLLEGE

AI AND PREJUDICE

I became concerned when reading "Spying on Your Emotions," John McQuaid's article on companies using artificial intelligence to analyze people's feelings. As an autistic person, I am hyperaware of the discrimination autistic individuals face in the workforce for what are, in essence, cultural differences between them and their neurotypical counterparts. The emotion-reading technology described sounds like it will reinforce the deep, if often unconscious, prejudices against autistic people that already exist.

Lack of eye contact is a common autistic trait that most neurotypical people believe indicates a lack of trustworthiness. The article did not allay my concerns when researcher Rosalind Picard related an anecdote about a colleague who disagreed with her and, to illustrate cluelessness, said that person "looked at my feet the whole time."

Michael A. Levine *via e-mail*

MERGING GALAXIES

"Cosmic Crashes," by Aaron S. Evans and Lee Armus, shows a simulation of the Milky Way and Andromeda colliding. No mention is made of dark matter, but it must have a significant effect on the dynamics of galaxy mergers. Do we know enough about it to make such detailed merger models?

Paul Colbourne *Ottawa*

Until now, I had not considered that galactic "collisions" only minimally involve component stars. As Evans and Armus explain, "most stars just pass right by one another during the event." I'm curious about those other poor stars that don't simply pass by. What effect do they have on the event?

Philip Jan Rothstein *Brookfield, Conn.*

THE AUTHORS REPLY: To answer Colbourne: There is still a lot about dark matter that is unknown, but it is thought that galaxies are surrounded by dark matter halos that explain the motion of their stars and of galaxies in groups and clusters. Dark matter makes up the vast majority of all matter but reveals itself only through gravity. Merger models routinely incorporate simple models of dark matter distribution, which greatly improves their ability to reproduce observed properties of galactic mergers, for example, by absorbing much of the orbital energy during the collision.

Regarding Rothstein's question: Stars are powered by fusion reactions in their core. The sun derives its energy by fusing hydrogen into helium. Stellar collisions can increase the mass of the remnant star, and more massive stars burn brighter and hotter, producing more energy. This happens in dense stellar clusters and could also be enhanced in a galactic merger. Yet these rare collisions would be energetically insignificant, compared with the energy generated by the nuclear starburst—or by a rapidly accreting supermassive black hole that just received a supply of fuel from the galactic merger. Both phenomena can easily surpass 100 billion times the sun's luminosity.

WORKING GROUP NEEDED

In "IPCC, Your Job Is Partly Done" [Observatory, November 2021], Naomi Oreskes calls for the closure of the physical science Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC). She argues that because human influence on global temperature is now clear, WGI's job is finished. We could not disagree more.

The world has just been surprised by a series of extreme climate events. Quantifying the human role in global heating is the beginning rather than the end of evaluating current and future risks to communities. The physical science evaluation of those risks is a cornerstone for societal action.

The IPCC's primary function is the assessment of scientific information that is sorely needed to make progress within the international United Nations Framework Convention on Climate Change (UNFCCC) and its policy instruments, particularly the Paris Agreement. Closing WGI would be a serious mistake and counterproductive in confronting the problem for three reasons.

First, attribution studies have evolved from global indicators to regional and local extreme climate events. These findings are extremely relevant to policy in the discussion of loss and damages at the level of the UNFCCC and beyond. Second, emerging kilometer-scale global and regional climate models have not yet been assessed, but they are a prerequisite for the next generation of the WGI Interactive Atlas on regional climate change, a key instrument for policy makers. Third, quantifiable information to evaluate adaptation and mitigation options requires the combination of physical and impact models. If vulnerable countries ask, for example, how their water resources will change in the coming decades, only carefully evaluated climate model information can deliver the key numbers on which policies should be based. The presence of a WGI community within the IPCC, providing this basis, remains indispensable for Working Groups II and III to fulfill their tasks.

The burden on the WGI scientists should indeed be reduced so that they can focus on the physical understanding needed to best support these policy needs with confidence. In our view, the problem is the proliferation of scenarios and the expectation that they be used with the latest and most expensive climate models. Since the fourth IPCC assessment cycle, this has created an unnecessary spiral in which valuable resources have been wasted. But comprehensive scientific assessments, including the physical science basis, will continue to clarify and inform and help to build the political will required to face this global challenge.

THOMAS F. STOCKER *University of Bern and co-chair, WGI, Fifth Assessment Report (AR5), IPCC*

SUSAN SOLOMON *Massachusetts Institute of Technology and co-chair, WGI, Fourth Assessment Report (AR4), IPCC*

QIN DAHE *China Meteorological Administration and co-chair, WGI, AR4 and AR5, IPCC*

VALERIE MASSON-DELMOTTE *University of Paris-Saclay and co-chair, WGI, Sixth Assessment Report (AR6), IPCC*

PANMAO ZHAI *China Meteorological Administration and co-chair, WGI, AR6, IPCC*

ERRATUM

"Radioactive Recycling," by Nikk Ogasa [Advances], incorrectly said americium and curium have forms that decay much more slowly than uranium. The most stable isotopes of americium and curium decay faster than uranium's most stable isotopes.

LETTERS TO THE EDITOR

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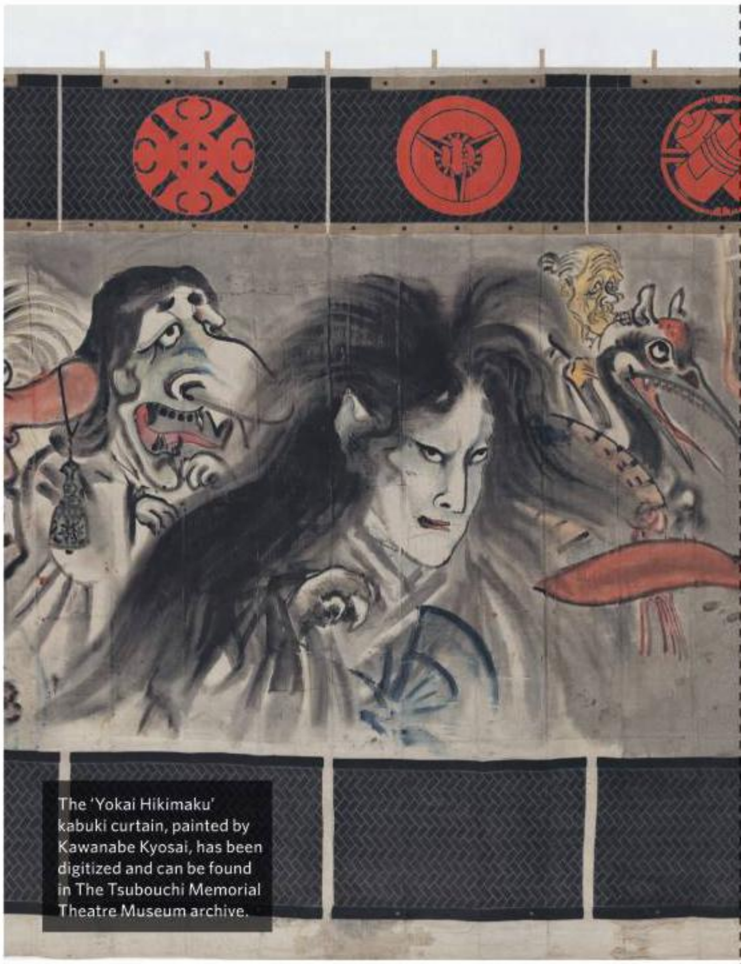
Home ground to Japan's living culture

A new library dedicated to the vivid imagination of novelist **HARUKI MURAKAMI** and an increasingly digitized, almost century-old **THEATER MUSEUM** showcase the strengths of Waseda University's cultural studies hub.



The 'Yokai Hikimaku' kabuki curtain, painted by Kawanabe Kyosai, has been digitized and can be found in The Tsubouchi Memorial Theatre Museum archive.

Walk into a bookshop nearly anywhere in the world, and you're almost certain to find a translation of one of Haruki Murakami's novels. His first book was published in 1979, while Murakami was running a small Tokyo jazz bar — Peter Cat — following a drama degree at Waseda University. Since then the writer has popularized Japanese literature at an unprecedented scale.

While Murakami certainly heightened international awareness of Japan's writers, his alma mater has long been a focal point for cultural activity, says Associate Professor Hitomi Yoshio. It has spawned a number of renowned authors and filmmakers, such as Yoko Ogawa, Yoko Tawada, and Hirokazu Kore-eda.

Last year, the university established a new literary resource center with a special dedication to Murakami's work, the Waseda International House of Literature (The Haruki Murakami Library).

This is one of many of the university's resources that help anchor the Global Japanese Studies Unit, one of seven units attached to the Waseda Goes Global project, which seeks to develop vibrant international academic networks. The center is also expanding its international collaborations as part of the Waseda Goes Global Plan, funded by the Japanese government's MEXT Top Global University Project.

Yoshio did her doctorate on Japanese women writers and the publishing culture of the early 20th century at Columbia University in the United States. In the last five years she's helped found English-language undergraduate and graduate degrees in Global Japanese Studies at Waseda. "Whether you're digging into archives of classical Japanese literature, or studying the contemporary subculture of Tokyo, it's the logical place to study Japanese culture," she explains.

Though Yoshio notes that popular subcultures such as manga and anime are the initial hooks for many students interested in Japan, upon entering the university they get to explore the country's literature, history, and underlying philosophies more deeply.

Yoshio has been overseeing Waseda's undergraduate Global Studies in Japanese Cultures Program (JCulP) since its inception in 2017. The annual intake has been divided between Japanese and overseas students, and this mixture is intentional. "The program is not about transmitting knowledge of Japanese culture from the inside to the outside. Sometimes it's the other way around," says Yoshio. "It's about questioning and rethinking established perceptions of Japanese culture from an outside perspective, and producing new interpretations together."

CULTURAL COLLECTIONS

Designed by architect, Kengo Kuma, with input from Murakami himself, the Waseda International House of Literature's sweeping shelves are stacked with an eclectic mix of literature in a huge range of languages. Murakami also donated furniture to a space that recreates his study, as well as a grand piano from Peter Cat, his original manuscripts, and book and record collections, all of which can be found in different parts of the library.

TSUBOUCHI EMPHASIZED THE IMPORTANCE OF PROMOTING A TRULY GLOBAL PERFORMING ARTS CULTURE.

The university has long recognized the value of preserving important cultural artifacts. In 1928, it established the Tsubouchi Memorial Theatre

Architect Kengo Kuma designed the Waseda International House of Literature.

Waseda alumni and authors, Yoko Ogawa and Haruki Murakami, discuss literature at a Waseda International House of Literature event.

Museum dedicated to Shoyo Tsubouchi (1859–1935), a former professor at Waseda, author, playwright, and the first person to translate the complete works of William Shakespeare into Japanese. Housed in an Elizabethan-style building modeled on the Fortune Playhouse in London, with an open stage at its front, the museum possesses more than one million items and showcases exhibits on everything from noh, kabuki, and kyogen theatrical forms to contemporary international plays. Today, the museum is also using the latest imaging technology to digitize materials and artifacts, including kabuki scripts and ukiyo-e woodblock prints, as well as noh masks which have been made into three-dimensional images. Many of these assets have been made accessible to the public.

"I think people are hungry for culture because of the COVID-19 pandemic," comments the museum's director, Professor Minako Okamuro. She says the pandemic has led to increased online archiving. In 2020, the museum established the Japan Digital Theatre Archives, an informational database and online repository of more than 1,300 Japanese theater performances. The museum also ran a successful exhibition in 2021 called 'Lost in Pandemic', which looked at the impact of COVID-19 on the performing arts, showcasing the posters and programs of canceled or postponed performances.

GLOBAL CONVERSATION

"The Tsubouchi Memorial Theatre Museum is dedicated to promoting the richness of Japan's theater and performing arts to the international community, but it also collects materials from around the world, such as magazines related to French theater and masks used in Indian dances," explains Okamuro.

"This was part of Tsubouchi's vision for theater. He emphasized the importance of not just highlighting Japanese theater culture, but also promoting a truly global performing arts culture."

Through projects like the Haruki Murakami Library and the Tsubouchi Memorial Theatre Museum, Waseda University's Global Japanese Studies Unit is laying the groundwork to reexamine Japanese culture from a genuinely global perspective. The university's goal is ultimately to become an international hub to promote scholarly and cultural exchange, and to share its knowledge and resources with the wider world. ■

WASEDA University

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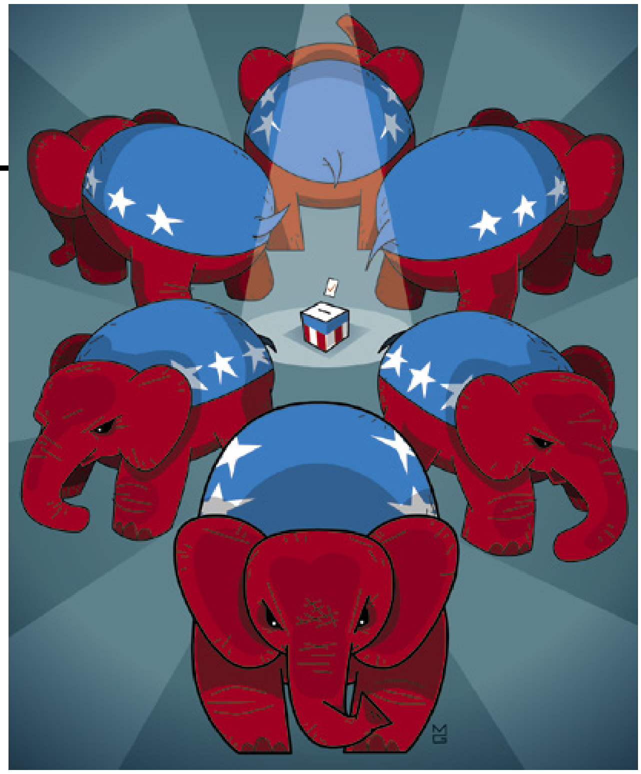
Protect Voting Rights

They boost suffrage, not fraud

By the Editors



In 2021 Republican legislatures in 19 states passed 34 laws that restricted access to voting in more than a dozen different ways. And those are just the bills that succeeded; hundreds of other provisions, some still under consideration, were introduced nationwide.

"The momentum around this legislation continues," the Brennan Center for Justice, which tracks these efforts, wrote on its Web site. At least 165 restrictive voting bills were already on the docket for this year by mid-January. "These early indicators—coupled with the ongoing mobilization around the Big Lie (the same false rhetoric about voter fraud that drove [last] year's unprecedented wave of vote suppression bills)—suggest that efforts to restrict and undermine the vote will continue to be a serious threat in 2022."

The GOP has justified voting restrictions by saying that it is safeguarding elections against fraud and that certain protections against electoral bias are no longer necessary. Evidence belies this ploy to seize power by disenfranchising voters, especially minorities, who tend to vote Democratic. Voter fraud is exceedingly rare in the U.S. and hasn't increased since the 1965 Voting Rights Act. But minority suffrage has grown tremendously, and the benefits of federal oversight have persisted. Alarmed by this trend, conservative legislators and jurists began chipping away at codified voting rights decades ago. They stand to gain even more ground during this year's midterm elections if left unchecked.

While odious lies about a stolen election propelled the current wave of restrictions, the path that led to this point was laid back in 2013. In the case of *Shelby County v. Holder,* the Supreme Court dismantled a key pillar of the Voting Rights Act called "preclearance," which required jurisdictions with a history of discrimination to get Justice Department or federal court approval for any planned changes to electoral rules. Arguing that patterns of discrimination had changed, Chief Justice John Roberts wrote in the majority opinion that Congress should not use "a formula based on 40-year-old facts having no logical relation to the present day."

Desmond Ang, an expert in public policy and race at Harvard University, disagrees, saying that preclearance is as essential to civil rights today as it ever has been. According to an analysis he published in 2019, that critical provision of the Voting Rights Act alone "continued to bolster enfranchisement over four decades later," especially among minorities. So enduring were the benefits, he wrote, that "broad preventative oversight encompassing the universe of potential voting changes may be the most effective means of curbing discrimination in settings like the United States, where electoral rulemaking is highly decentralized and opaque."

In a similar vein, sociologists Nicholas Pedriana and Robin Stryker concluded in a 2017 comparative analysis that of three seminal civil rights laws passed in the 1960s—the Voting Rights Act, the Fair Housing Act and the equal employment opportunity provisions of the Civil Rights Act—the Voting Rights Act was the most successful in promoting equality. Its success depended largely on what the researchers called group-centered effects, which focus on systemic disadvantage rather than individual harm, discriminatory consequences rather than intent, and remedial group results rather than justice for individual victims or wrongdoers. Removing that statutory framework produces the opposite effect, Stryker says: highly effective, systematic suppression of minority votes.

In January the Democrats' best efforts to date to repel the current onslaught of voting restrictions—the Freedom to Vote Act and the John R. Lewis Voting Rights Advancement Act—failed in the Senate. The former would have established nationwide standards for ballot access and hindered other forms of electoral prejudice such as gerrymandering. The latter would have reversed the 2013 Supreme Court ruling on preclearance as well as another one last year, which made it harder to challenge electoral rules in court on the grounds of discrimination. The bills contained the type of broad-based, preventive strategies that have been so effective at fostering racial equality at the very core of our democratic system. Ang and Stryker lamented their demise and conceded that it's difficult not to despair in the face of intense political polarization.

For decades the Voting Rights Act enjoyed bipartisan support. No longer. Yet we must restore and expand federal oversight and jurisdiction of biased electoral rules. Until then, it is incumbent on social justice movements and everyone who cares about the most fundamental of democratic rights to keep the pressure on. As sociologist Aldon Morris wrote for us in February 2021, "when President Lyndon B. Johnson formally ended the Jim Crow era by signing the Civil Rights Act in 1964 and the Voting Rights Act in 1965, he did so because massive protests raging in the streets had forced it."

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Illustration by Martin Gee

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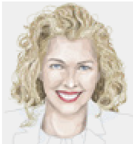

Nathalie Goodkin is a chemical oceanographer and an associate curator at the American Museum of Natural History. **Julie Pullen** leads initiatives in climate risk and climate solutions. She is an adjunct research scientist at Columbia University's Earth Institute.

Let Oceans Breathe

Marine oxygen levels are the next great casualty of climate change

By Nathalie Goodkin and Julie Pullen

Last summer, in an unseasonal event, more than 100 miles of Florida's coast around Tampa Bay became an oxygen-depleted dead zone littered with fish along the nearby shoreline. In the Northwest, Dungeness crabs were washing onto Oregon's beaches, unable to escape from water that has, in dramatic episodes, become seasonally depleted of oxygen over the past two decades.

Much of the conversation around our climate crisis highlights the emission of greenhouse gases and their effect on warming, precipitation, sea-level rise and ocean acidification. We hear little about the effect of climate change on oxygen levels, particularly in oceans and lakes. But water without adequate oxygen cannot support life, and for the three billion people who depend on coastal fisheries for income, declining ocean oxygen levels are catastrophic.

As ocean and atmospheric scientists focused on climate, we believe that oceanic oxygen levels are the next big casualty of global warming. To stop the situation from worsening, we need to expand our attention to include the perilous state of oceanic oxygen levels—the life-support system of our planet. We need to accelerate ocean-based climate solutions that boost oxygen, including nature-based solutions such as those discussed at the 2021 United Nations Climate Change Conference (COP26) held in Glasgow.

As the amount of carbon dioxide increases in the atmosphere, not only does it warm air by trapping radiation, it warms water. The interplay between oceans and the atmosphere is complex, but to put it simply, oceans have taken up about 90 percent of the excess heat created by climate change during the Anthropocene. Bodies of water can also absorb CO_2 and oxygen but only up to a limit: warmer water holds less oxygen. This decrease in oxygen content, coupled with a large-scale die-off of oxygen-generating phytoplankton resulting not just from climate change but from plastic pollution and industrial runoff, compromises ecosystems, asphyxiating marine life and leading to further die-offs. Large swaths of the oceans have lost 10 to 40 percent of their oxygen, and that loss is expected to accelerate with climate change.

The dramatic loss of oxygen from our bodies of water is compounding climate-related feedback mechanisms described by scientists in many fields, hundreds of whom signed the 2018 Kiel Declaration on Ocean Deoxygenation. This declaration has culminated in the new Global Ocean Oxygen Decade, a project under the U.N. Ocean Decade (2021–2030). Yet despite years of research into climate change and its effect on temperature, we know comparatively little about its effect on oxygen levels and what falling oxygen levels, in turn, may do to the wider earth system.

As the financial world invests in climate change solutions, possibly including future geoengineering efforts such as iron fertilization, we run the risk of exacerbating oxygen loss. We need to evaluate potential unintended consequences of climate solutions for the full life-support system.

Fish die-off at Madeira Beach, Fla., July 2021

Octavio Jones/Getty Images

Beyond enhanced monitoring of oxygen and the establishment of an oxygen-accounting system, such an agenda encompasses fully valuing the ecosystem co-benefits of carbon sequestration by our ocean's seaweed, seagrasses, mangroves and other wetlands. These so-called blue carbon nature-based solutions are also remarkable at oxygenating our planet through photosynthesis. At COP26 we saw a lot of primarily terrestrial initiatives and commitments, such as for forestry management, that are excellent steps forward. We hope the 2021 climate conference and this year's COP27 meeting help oceanic nature-based solutions to come into their own, propelled by the U.N. Ocean Decade.

Putting oxygen into the climate story motivates us to do the work to understand the deep systemic changes happening in our complex atmospheric and oceanic systems. Even as we celebrated the return of humpback whales in recent years to an increasingly clean New York Harbor and Hudson River, dead fish clogged the Hudson in the summer as warmer waters carried less oxygen. Ecosystem changes connected to physical and chemical systems-level data may point the way to new approaches to climate solutions—ones that encompass an enhanced understanding of the life-support system of our planet and complement our understanding of drawdown to reduce emissions of CO_2. Roughly 40 percent of the world's people depend on the ocean for their livelihoods. If we do not save marine life from oxygen starvation, we starve ourselves. SA

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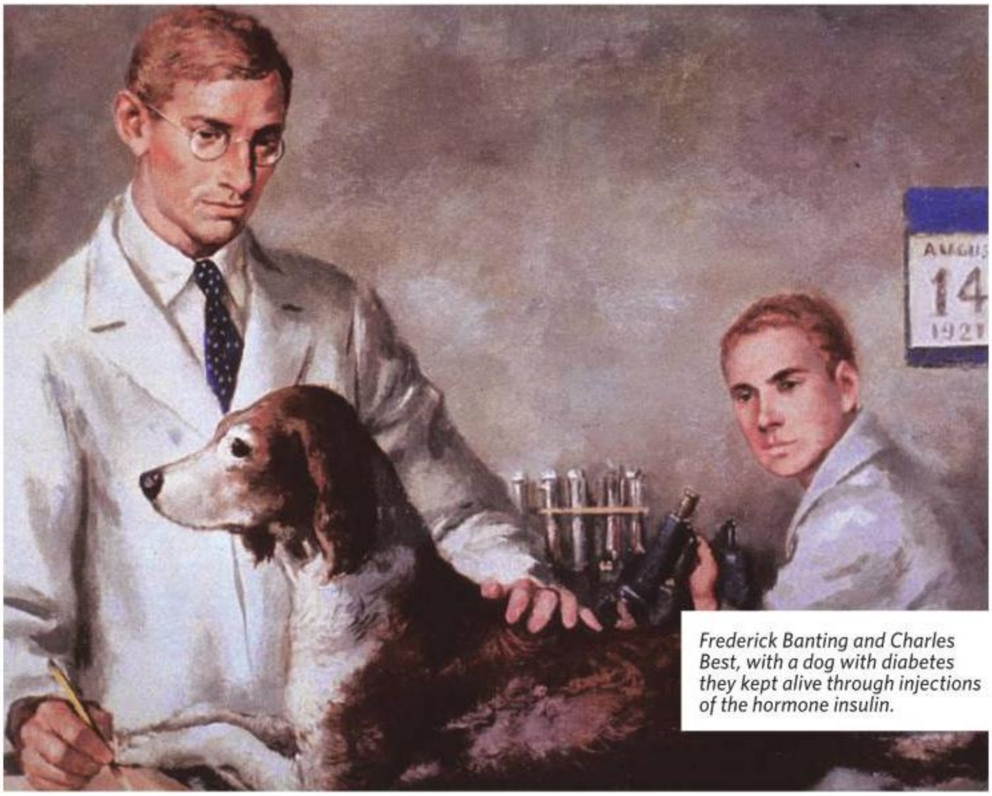
THE NEXT 100 YEARS OF DIABETES CARE

On the anniversary of the discovery of insulin, experts reflect on how much progress has been made to treat and manage diabetes—and how much more is necessary.



Frederick Banting and Charles Best, with a dog with diabetes they kept alive through injections of the hormone insulin.

CREDIT: EVERETT COLLECTION HISTORICAL / ALAMY

The first description of diabetes was recorded in Egyptian medical texts around 552 BC. But, as recently as a century ago, the most effective treatment available was a strict low carbohydrate diet, which wasn't terribly effective. People with diabetes tended not to live long.

That changed 100 years ago, when Canadian surgeon, Frederick Banting, and his assistant, Charles Best gave purified insulin from cows to Leonard Thompson, a 14-year-old boy with type 1 diabetes. The pair's work demonstrated that insulin could reduce blood glucose levels. The work earned them a Nobel Prize and more importantly, it saved Thompson's life, and millions since.

"MORE PEOPLE LIVING WITH DIABETES MEANS MORE PEOPLE DEVELOPING COMPLICATIONS"
—Katherine Tuttle

Since that discovery, advances in diabetes treatment have arrived in rapid succession, with synthetic insulin, glucose monitors, insulin pumps and other innovations. Even so, diabetes, and in particular type 2 diabetes, remains a large-scale epidemic: globally, more than 537 million people live with diabetes, according to the International Diabetes Federation. Diabetes is also strongly associated with cardiovascular disease, to the extent that among those with type 2 diabetes, it is the leading cause of death.

At the moment, the field is at a juncture. Diabetes treatment options have never been better, but diabetes rates have never been higher. With the next 100 years starting now, what lies ahead?

A growing crisis

In November, *Scientific American*'s Custom Media division hosted an expert panel to examine the disease burden of type 2 diabetes, along with complications, and treatments. The session included three leading experts in diabetes and was part of a series supported by Know Diabetes by Heart, a joint initiative between the American Heart Association and the American Diabetes Association.

Incidence of diabetes has far outpaced projections. In the U.S., one in 10 adults—34.2 million—have diabetes. "For those 65 and older, that number becomes nearly 30 percent," said Boris Draznin, an endocrinologist and director of the adult diabetes program at University of Colorado School of Medicine, at the event.

Mikhail Kosiborod, a cardiologist at St. Luke's Mid-America Heart Institute and professor of Medicine at the University of Missouri Kansas City, was also a panelist at the event. He explained that most scientists agree the sharp increase in type 2 diabetes is due, largely, to "skyrocketing rates of obesity." In 1999, 30 percent of Americans were obese; that figure rose to 42 percent by 2018. With excessive weight gain, many people develop insulin resistance, which elevates glucose levels in the blood, and leads to diabetes.

"More people living with diabetes means more people developing ... complications," said Katherine Tuttle, a nephrologist at Providence Health Care and professor of Medicine at the University of Washington, at the event. The most dangerous are chronic kidney disease and what she calls "a tsunami of cardiovascular conditions."

The healthcare costs, too, are staggering. In 2017, the American Diabetes Association estimated the yearly cost of diagnosed cases at $327 billion, with one out of every seven health care dollars spent treating diabetes or its complications. Kosiborod said that on the current trajectory he is concerned that "we're not going to have enough resources to provide proper care for everybody."

Getting ahead of diabetes

All three experts discussed the urgent need to better educate the public about diabetes. A recent Harris poll revealed more than 60 percent of people surveyed were aware of associated heart and kidney disease risks.

In general, Tuttle said, "People don't take [diabetes] as seriously as they should. By the time that we see these patients, they often have very advanced disease."

For decades, the American Diabetes Association and other organizations have recommended that doctors test patients yearly for albumin, a protein which, when found in urine, is an early marker of kidney damage and a possible predicator of heart problems. Depending on the setting, just 10 to 40 percent of patients are tested.

While diagnosis and treatment are critical, prevention is perhaps even more so. "Lifestyle is the cornerstone on which everything is built," Draznin said. That is often easier said than done. "If you live in a place where it's unsafe to walk or can't obtain or afford healthy foods, then the deck is already stacked against us," Tuttle said. "I think that we need major societal and cultural shifts to support people. Public health needs to be a priority."

"LIFESTYLE IS THE CORNERSTONE ON WHICH EVERYTHING IS BUILT."
—Boris Draznin

Advances in treatment

For those who have diabetes, Kosiborod said the objective of health care professionals is to "make our patients live longer and feel better."

The ability to reach those goals improved greatly with the introduction of new, better forms of insulin. An unexpected result of large clinical trials that began in 2008 had been the identification of medications that better prevent further complications, including heart attack, stroke, heart failure and kidney disease. Some of these drugs can do all of those things, including SGLT2 inhibitors (sodium-glucose cotransporter-2).

Such research has transformed diabetes management into "one of the most evidence-based [fields] in the entirety of medicine," Kosiborod said. "We're living in an age of renaissance... with many highly efficacious and well-tolerated treatments that can be life-changing for patients with diabetes."

While there is more to be discovered about the precise mechanisms of the disease, treatment is moving towards a more holistic approach. "This is really a syndrome, a systemic condition that affects multiple organs," he said.

Technology has also revolutionized treatment with continuous glucose monitoring devices. "They allow people to see exactly what happens after they eat...what happens with their glycemic control during exercise or during an afternoon nap," Draznin said.

"THIS IS REALLY A SYNDROME, A SYSTEMIC CONDITION THAT AFFECTS MULTIPLE ORGANS."
—Mikhail Kosiborod

THE EXPERTS WEIGH IN

- **Boris Draznin,** *Endocrinologist & director of the adult diabetes program at University of Colorado School of Medicine*
- **Katherine Tuttle,** *Nephrologist at Providence Health Care & professor of Medicine at the University of Washington*
- **Mikhail Kosiborod,** *Cardiologist at St. Luke's Mid-America Heart Institute & professor of Medicine at the University of Missouri Kansas City*

Yet for all this good news, the current pandemic has revealed cracks in the healthcare system for those with diabetes. COVID-19 is much more likely to severely impact patients with diabetes and associated conditions, such as heart and kidney conditions and obesity. That translates into a more severe illness with higher risk of complications, hospitalization and loss of life.

The pandemic has also highlighted the need for prevention and education in addition to acute care. Making sure that all receive needed care will require stronger public policy and support from insurance companies, Tuttle said. "When we have treatments like this, how can we not let people know—and not deliver these therapies?" she asked.

"It really is time that we have a call to action about this."

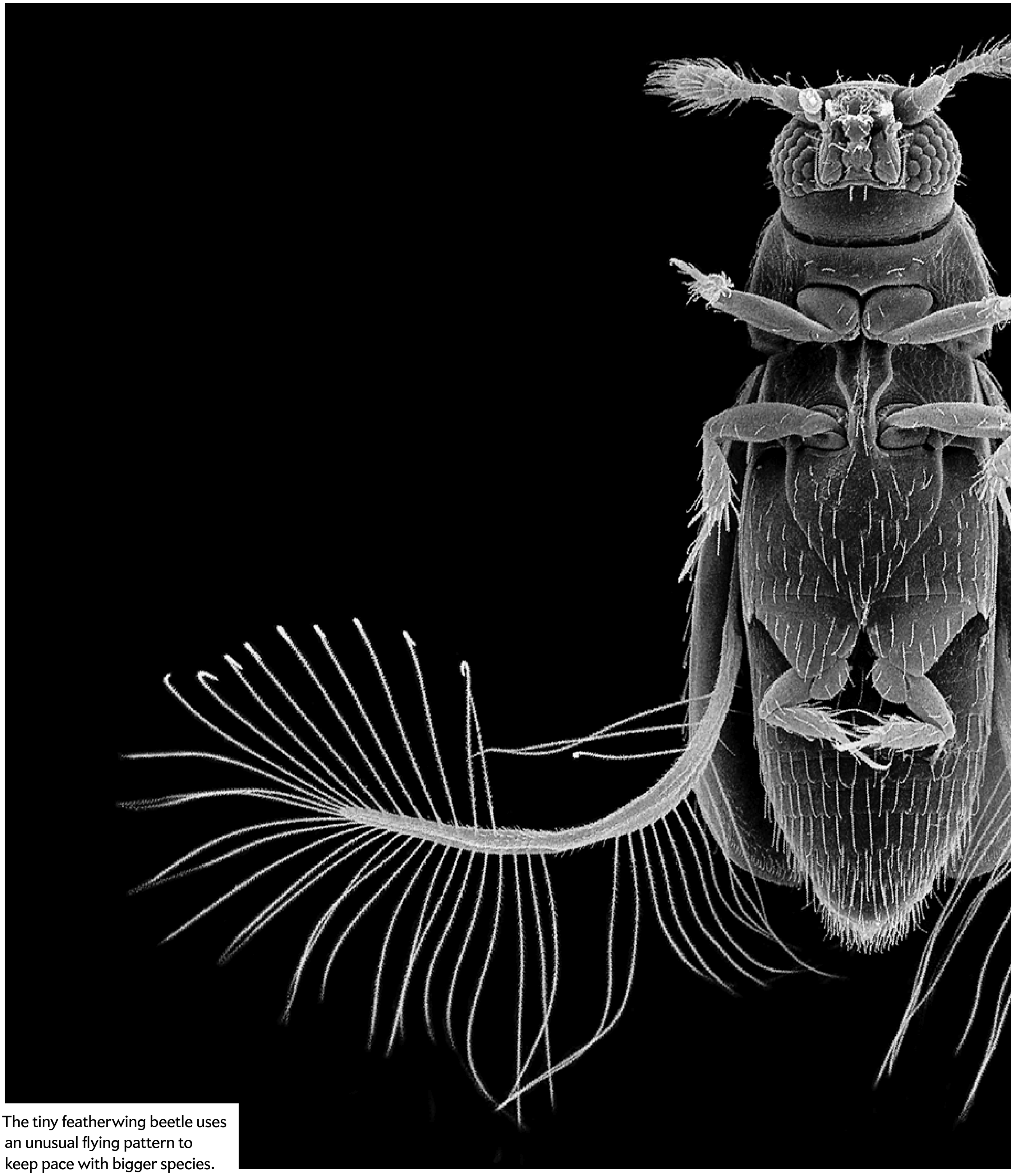
To watch the event, visit scientificamerican.com/custom-media/the-next-100-years-of-diabetes-care. For the latest information, guidelines for clinicians, and other resources on how to manage diabetes and CVD, visit KnowDiabetesbyHeart.org.

American Heart Association.

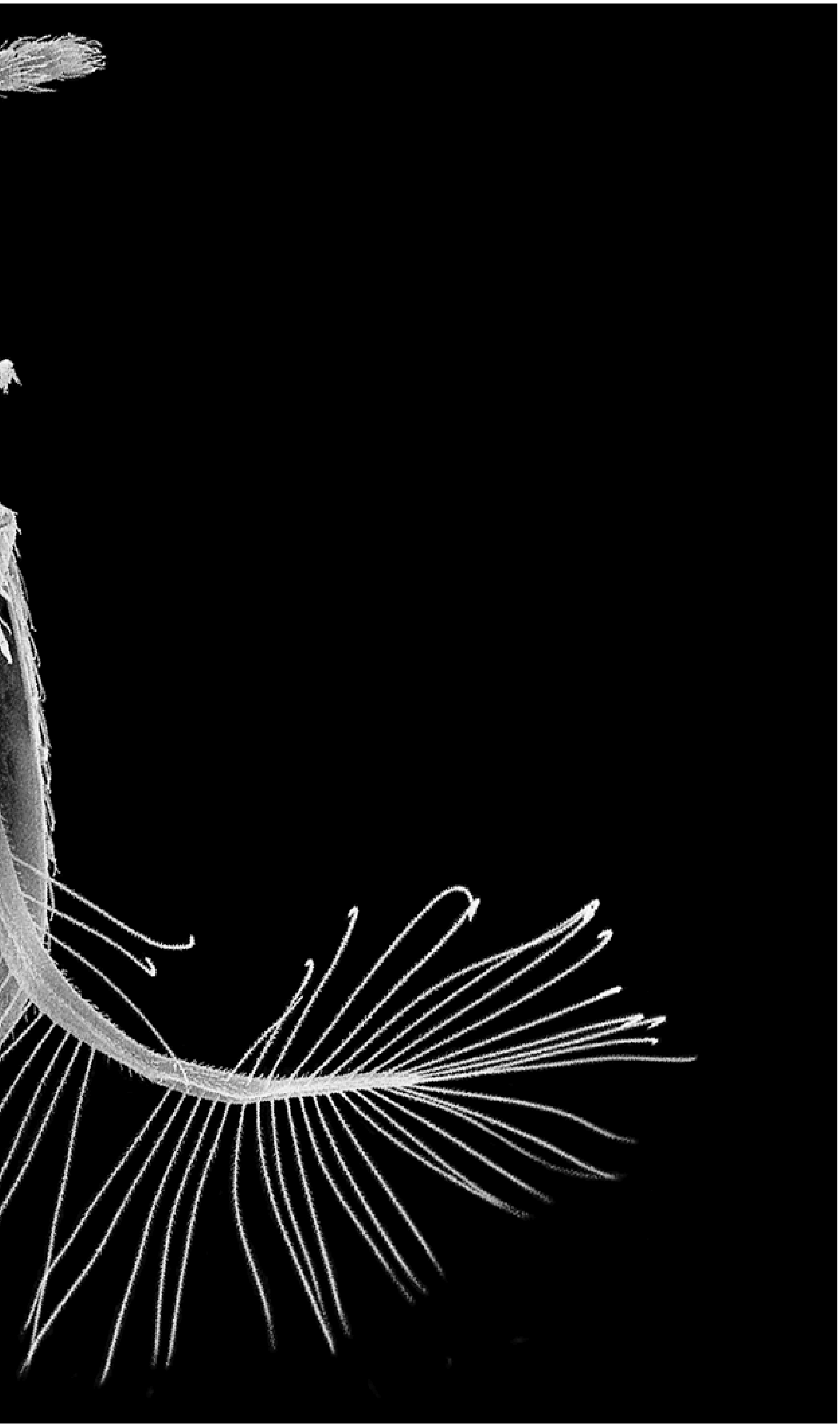
American Diabetes Association. Connected for Life

Know Diabetes by Heart™

ADVANCES



The tiny featherwing beetle uses an unusual flying pattern to keep pace with bigger species.



From "Novel Flight Style and Light Wings Boost Flight Performance of Tiny Beetles," by Sergey E. Farisenkov et al., in *Nature*, Vol. 602; February 3, 2022

INSIDE

AERODYNAMICS

Flying Tiny

A speck-sized beetle turns flight mechanics upside down

When it comes to insect flight, bigger is usually better. As wings shrink, air friction overwhelms flight power—that's why dragonflies soar as houseflies sputter. But a beetle the size of a grain of sand flips this maxim on its head.

The featherwing beetle (*Paratuposa placentis*), less than half a millimeter long, is smaller than some single-celled amoebas. At this scale air becomes syrupy, and scientists once believed the beetles simply drifted wherever the wind blew them. But new research in *Nature* shows how they wield lightweight wings to keep pace with species three times their size.

As the name suggests, featherwing beetles sport bristled, featherlike wings. These porous appendages are light and produce less friction than the typical membrane-based wings that flies have, helping the beetle generate lift. Multiple insect lineages, including parasitic wasps, have evolved similar wings as they downsized—but these beetles use a previously unknown strategy to generate their outsized flight prowess, according to the new study's authors.

In 2017 the research team collected featherwing beetles from bits of fungi in a Vietnam jungle. To record the insects' infinitesimal flight patterns, experimenters placed the creatures in a transparent chamber and filmed them with two high-speed cameras at nearly 4,000 frames per second during a battery of tests. They used these recordings to construct 3-D models of the diminutive beetle and calculate its aerodynamics.

The team found that instead of flapping their wings up and down, featherwing beetles loop them in a "remarkable" figure-eight pattern, says study co-author Dmitry Kolomenskiy, a physicist studying fluid mechanics at Moscow's Skolkovo Institute of Science and Technology. After the bristled wings unfurl from their protective cases, known as elytra, they mirror each other as they move, clapping together both in front of and behind the insect—Kolomenskiy says the motion is reminiscent of an extreme version of swim strokes such as the butterfly. The elytra stabilize the beetle and its churning wings, preventing it from spinning.

The pattern's resemblance to swimming particularly intrigues Arvind Santhanakrishnan, a mechanical engineer who studies tiny insects' aerodynamics at Oklahoma State University. "Typically this type of paddling is seen in small aquatic crustaceans such as water fleas," says Santhanakrishnan, who was not involved with the study. "It was quite surprising to see that a similar strategy was used by the tiny featherwing beetles to generate lift."

Kolomenskiy and his colleagues hope to illustrate the flight patterns of other, similarly minuscule insects. They say their findings may influence how engineers shrink flying technology—although Kolomenskiy admits it would take a major engineering feat for a drone to approach the proportions of a featherwing beetle. "Probably not as small," he says. "But that's to be explored."

—Jack Tamisiea

MICROBIOLOGY

Genes under Wraps

An ancient molecule helps bacteria take control of their genome

DNA has a knotty problem. Thousands of times longer than the cell that contains it, this intricate strand of As, Ts, Gs and Cs must fold itself into a compact package. But the thin double helix molecule can't jam itself in any which way, lest it wind up horribly knotted. What's more, the cell needs certain segments of the strand—particular genes—to remain accessible to protein-making machinery while keeping others tucked away and turned off. It's like playing Tetris with a tangled ball of yarn.

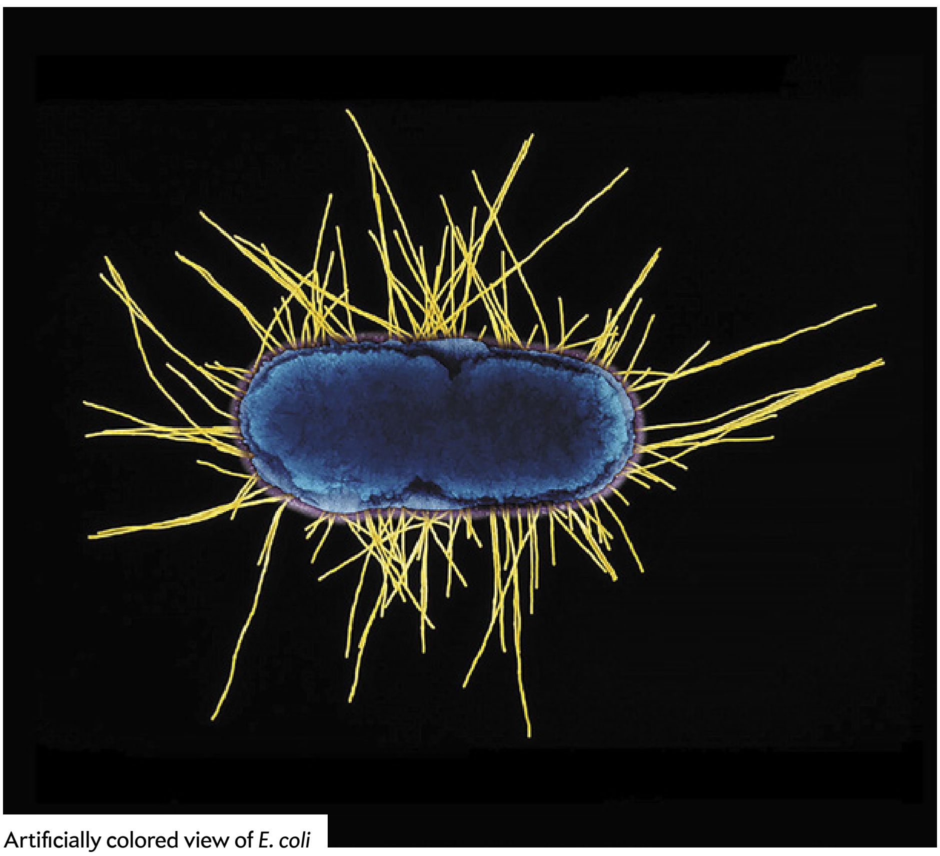
Nucleus-containing "eukaryotic" cells, the type found in humans, plants and animals, rely on complex interactions between chemical tags and specialized proteins to provide instructions about what genes to turn on and when—a system called epigenetics. For decades scientists thought epigenetic regulation was unique to eukaryotic cells and lacking in simpler ones, such as bacteria. But a series of newer findings has challenged that idea.

"Bacteria are way more sophisticated than anyone realized," says David Low, a microbiologist at the University of California, Santa Barbara.

New studies by University of Michigan biochemists Ursula Jakob and Peter Freddolino reveal that interactions between DNA-binding proteins and an ancient molecule called polyphosphate help to switch bacteria's genes on and off on a broad scale. Not only do these findings tell scientists more about such organisms' basic biology, but they could also help researchers fine-tune genetically engineered bacteria for biotechnology—and even contribute to new antibiotics.

"Bacteria are carrying around the seeds of their own destruction, and we might be able to remove the repression that's keeping [those seeds] down," Freddolino says.

Eukaryotic cells have long been known to use multiple layers of regulation, controlling which genes are active and how much of a given protein each one makes. Bacterial DNA, on the other hand, was typically portrayed in textbooks as a long piece of inert string, wait-



Artificially colored view of *E. coli*

wangshin Kim/Science Source

ing to be transcribed. That idea began to unravel in 1994, when Low discovered that a chemical tag called a methyl group could block transcription in bacteria—something scientists had thought was exclusive to eukaryotic cells.

More similarities have emerged over the years. For example, eukaryotic cells attach chemical tags and proteins called histones to hide away parts of the genome. Last year Freddolino's laboratory showed that bacteria use an analogous strategy: the researchers identified 200 regions in the *Escherichia coli* genome that are silenced using chemical tags and structures called nucleoid-associated proteins (NAPs).

For a recent study in the *EMBO Journal*, Freddolino demonstrated that NAPs worked similarly to silence specific sections of the bacterial genome in distantly related species *E. coli* and *Bacillus subtilis*. The NAP acts as a scaffold around which a portion of DNA gets wrapped, making it physically impossible for the cell's protein-making machinery to access genes in that portion. This effect is critically important for bacteria: it allows them to seal off snippets of outside DNA and viruses that have wedged their way into the bacterial genome, and it lets them wall off rarely used genes when they are not needed.

NAPs do not work alone, however. To determine what triggers them to switch off sections of DNA, Freddolino and Jakob turned their attention to polyphosphate. This molecule was used for energy storage by Earth's early life and has evolved a variety of functions in cells. In 2020 Jakob found that mutant *E. coli* unable to synthesize polyphosphate showed more activity in genes absorbed from outside the cell—and that this activity plays a key role in cell death from DNA damage.

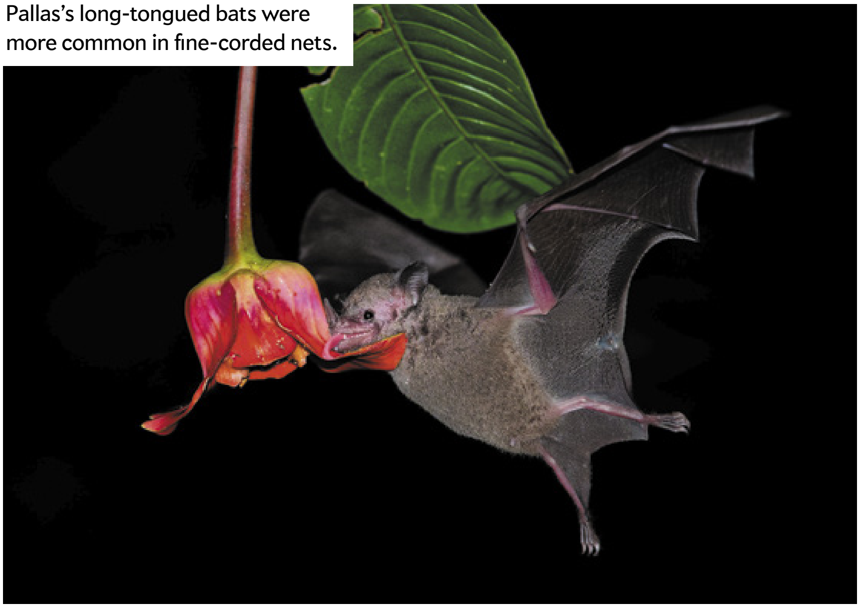
Recently, in *Science Advances*, Jakob and Freddolino showed that negatively charged polyphosphate binds to positively charged NAPs using a process called liquid-liquid phase separation, in which ultradense protein groups condense into tiny droplets. As more and more polyphosphate attaches to the NAPs, the normally scattershot structure of polyphosphate, NAPs and DNA becomes organized. Just as oil droplets can form in even a well-mixed vinaigrette, droplets of protein, DNA and polyphosphate can congeal in bacterial cells—and this blocks parts of the genome from transcription. The process does not need additional helper proteins, and it can be reversed when polyphosphate levels drop.

These studies are a major step in understanding bacterial epigenetics, says University of Leiden biochemist Remus Dame, who was not involved in either study. "There's good reason to believe that the global structure in which these genes are embedded dictates how active they are," he says. "This is really something very new—and very hot—that means we have to look differently at our system of interest."

Freddolino says that when his biotechnology-focused colleagues first learned of these results, they began using this knowledge to insert engineered genes into spots along the bacterial genome that optimize protein production. The process, he says, has since gone from "cross your fingers and hope for the best" to a sound strategy that works almost every time.

At the Massachusetts Institute of Technology, biochemist Peter Dedon is investigating how scientists can make new antibiotics using these mechanisms. Work from his lab (and others around the world) shows that bacteria switch genes on and off to help infect hosts—and to resist antibiotics. Dedon envisions a small molecule that could interfere with this process and keep a bacterium's infection-boosting characteristics or antibiotic resistance genes switched off; another option would be to disrupt polyphosphate's ability to bind to NAPs. This would not kill bacteria outright, but it would render them less able to cause disease and more susceptible to immune system attacks. "There's great potential there," Dedon says. "There's a whole new world of antibiotic targets."

Bacterial epigenetics is an excellent focus for antibiotic development, Jakob says, because its mechanisms are shared across many bacteria species—but use fundamentally different proteins than eukaryotic cells do. This means researchers can specifically target bacterial proteins and avoid interfering with the body's own epigenetic processes, Jakob says: "It's a way to prevent disease without needing to kill the cell." —*Carrie Arnold*



Pallas's long-tongued bats were more common in fine-corded nets.

RESEARCH METHODS

Bat Inspection

Switching equipment can dramatically alter scientific results

Last year biologist Gloriana Chaverri and her students confirmed a hunch about trapping bats to study and release. They experimentally hung fine-corded monofilament nets in Costa Rican foliage, snagging 125 bats from 20 species. Meanwhile typical, thicker-stranded nets captured only 90 of the flying mammals from 14 species. In *Royal Society Open Science,* her team from the University of Costa Rica and Smithsonian Tropical Research Institute explores how equipment choice can influence what scientific expeditions reveal. And Chaverri says that although the finer nets changed the researchers' group dynamics—there was less chatting because they had to pay more attention to extract bats from the tangle-prone web—monofilament nets are now a fixture in her tool kit.

Scientific American spoke with Chaverri about bat-catching protocols, elusive insectivores and what new takes on old technology can reveal about an ecosystem's inhabitants.

—Leslie Nemo

How do you hang nets to catch bats in the wild?

The best places are cluttered but not so much so that the bats are not flying along those routes. If the area is devoid of vegetation, then the bats will very easily detect the net. The nets are always hanging close to the ground, and if you're not experienced, stretching the nets takes a long time because you need to be very careful—they get tangled in your clothes.

The best time to open a net is right at sunset because the bats are so hungry by the end of the day that you get the majority captured between six and eight [P.M.] here in Costa Rica. Usually we try to stay until midnight. For the regular nets people have been using for years, the threads are resistant to the bites from most species of bats, so we open up the nets and then keep visiting them every 15 to 20 minutes.

What made you want to formally test the differences between the older, thicker nets and monofilament ones?

The first time I saw this type of net was in 2013 at a bat meeting in Costa Rica. I'm always up for trying new things, so I purchased one. I went out one time, I placed the net, and all of a sudden I was capturing these species that I had never captured before. I started thinking: "Hmm—this is interesting."

I did a project a few years back in Uruguay, and we purchased only monofilament nets. I was presenting the results to other bat researchers, and they asked me, "How on Earth were you able to capture so many bats?" I showed them the nets, and they were all very excited. That's another point that made me think maybe this should be published, because a lot of people don't know about the availability of this other net.

What did you find when you specifically compared the two nets?

I think the differences were very noticeable. The main thing is the species that we're getting: the regular nets are missing a lot of the insectivorous bats that we normally see very rarely. Untangling bats from a monofilament net really is more challenging overall. The threads are difficult to see, so if researchers are not careful they could unintentionally pull a thread tangled around soft tissues and hurt the bat.

Another study recently compared different net designs and found that very fine nets were less successful. Why do you think that is?

The bats are good at chewing up the monofilament net and getting released. [The other research team] checked the nets as if they were regular nets, every 15 or 20 minutes, [compared with our study's] every two to five minutes. Sometimes you don't have enough field personnel to be checking the nets so often. I think the combination of our two papers shows the pros and cons of using the monofilament nets ... and will allow a lot of people to start thinking more about what equipment to use, based on the questions they have. People place [traditional nets] and assume that whatever they're getting is what's out there. Of course, many studies show that's not true—but we still use them.

How big a role do equipment choices like these play in what you learn?

Oof—yeah, they play a big role. [Papers suggest] we're missing a big part of the bat assemblages that we have, for example, in the Neotropics.... I think the monofilament nets are one of those instruments that we have to take advantage of, especially because they're fairly cheap and easy to use. I keep telling everyone about these nets. Whatever way I can help researchers reach conclusions that are closer, more or less, to the truth, I think that's definitely a good thing for everyone.

photorip/Getty Images

ENVIRONMENT

Ancient Hazard

Toxic algae may have plagued Maya society

Maya civilization once stretched hundreds of miles across Mesoamerica and the Yucatán Peninsula, with bustling cities, a thriving economy, and a booming arts and culture scene. But between the eighth and 10th centuries C.E., it endured sudden population fluctuations, increased conflict and abandoned urban centers. Archaeologists and other researchers have considered landscape degradation, volcanoes and drought as possible drivers of this dramatic instability throughout Maya society.

For a recent study in the *Proceedings of the National Academy of Sciences USA*, researchers probed a lake bed near the ancient Maya city of Kaminaljuyú to investigate another possible stressor: harmful algae in the water supply. Chemicals called cyanotoxins, which make some algae blooms poisonous, were preserved in sediments at the bottom of central Guatemala's Lake Amititlán—along with green pigments that record algae's presence. Study lead author Matthew Waters, a limnologist at Auburn University, and his colleagues sampled a 5.5-meter core of lake-bed muck and found a 2,100-year record of algae blooms, possibly caused by runoff from settlements and farms in the watershed. The findings suggest these toxic blooms would have rivaled their modern counterparts. In Lake Amititlán (which frequently hosts harmful algae blooms today), cyanotoxin concentrations rose throughout the period in which Maya civilization reached—and then fell from—its zenith. A previous study showed ancient algae in a lake near the Maya city of Tikal, but Waters says his team's is the first to provide definitive evidence of cyanotoxins.

Kaminaljuyú today

The Maya were concerned about contaminated water reservoirs as early as C.E. 200, says Liwy Grazioso, an archaeologist at the Universidad de San Carlos de Guatemala who was not involved in the new study. "They knew from observing nature that there were episodes when the water did not have good quality," she says, "so they brought in sand from 30 kilometers away to create a filtering system."

Today's scientists are just beginning to grasp the extent of water-quality issues during the period of Maya instability. Because that time span featured widespread droughts, Waters says, quantity of water has been studied more than quality. The blooms alone were likely not responsible for societal instability, he notes—but having toxic reservoirs amid the droughts could not have helped.

Together with research on the makeup of ancient algae blooms, Waters adds, the study "starts to build a case that water quality and water potability need to be added to the list of environmental stressors" on Maya civilization. Lake Amititlán's history provides a stark reminder to carefully manage land, as well as water, to avoid pitfalls of the past. *—Rebecca Dzombak*

Top of Nestawedjat's innermost coffin

ANTHROPOLOGY

Mummy Match

Forensic analysis connects an Egyptian woman with her intricate resting place

A mysterious mummy's artificial eyes—placed to help her see in the afterlife—would have shown her quite a lot over the past 2,700 years.

Researchers examining the mummy at the British Museum thought the remains were male after x-ray images from the 1960s revealed dense packing in its crotch area. But a potentially matching trio of beautifully detailed nesting wood coffins, acquired with the mummy as a set, bore hieroglyphics describing a female homemaker named Nestawedjat. She lived in what is today Luxor, in roughly 700 B.C.E. during Egypt's 25th dynasty, when it was ruled by Kushite pharaohs from Sudan.

For a recent study in the *Journal of Archaeological Science: Reports*, curator Marie Vandenbeusch and her colleagues set out to verify whether the mummy and coffins really belonged together. Their first clue came from CT scans that revealed the mummy was female, matching the coffins' description. They then analyzed the chemical makeup of black embalming residue in the innermost coffin's left shoulder area. This substance's ingredients—mostly wax, oil and fat—had identical proportions to residue found on the mummy's left shoulder.

"It's quite a lot of detective work to bring all that together" and determine a mummy's origin, Vandenbeusch says. She notes that mummies are commonly found outside of coffins in old collections; this process could make them easier to test for potential matches. (The study's CT scans also spotted the mummy's artificial eyes, made from two different materials that might be glass or stone.)

Ronald Beckett, a Quinnipiac University biomedical scientist who was not involved in the study, says this "rigorous methodology" using chemistry "adds clarity to the origins, identities and relationships among ancient remains." Moreover, "the analysis of the constituents of embalming concoctions contributes to our understanding of ancient methods of preparing the dead."

It is unclear why Nestawedjat was removed from her coffins, but Vandenbeusch's archival research suggests that a British colonel acquired the remains in Egypt on his way to India in the mid-19th century. He died in India, but Nestawedjat ended up in London—where she is now reunited with her coffins.

—Joshua Rapp Learn

Ton Koene/Alamy Stock Photo (*left*); South China Morning Post/Getty Images (*right*)

BIOTECHNOLOGY

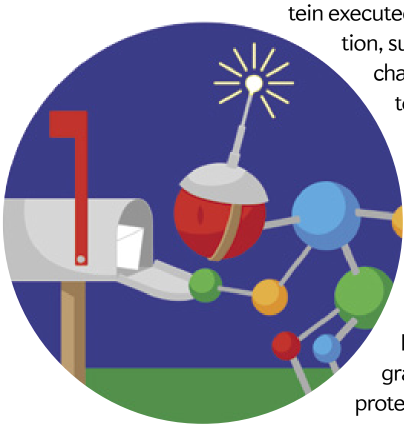
DNA Antennas

Nanoscale indicator may speed up drug design

Developing drugs can be hit or miss, but now a tiny, DNA-based sensor may help streamline the task. Acting as a "fluorescent nanoantenna," the sensor could flag in real time if a prospective drug is binding to its target or reveal other cellular activity.

Cells use protein molecules to communicate with one another and trigger functions throughout the body. When such a message comes into contact with a cell's surface protein, one of the molecules involved changes shape like a lock opened by a key, prompting a reaction. At just five nanometers across—one 200th the length of a typical bacterium—fluorescent nanoantennas can bind to and interact with proteins on a molecular level. Each nanoantenna can target a particular protein; when that protein changes shape, the bound nanoantenna shifts as well and emits specific light when viewed under a fluorescence microscope.

For a study in *Nature Methods*, researchers put these new nanoantennas to work flagging when a particular digestive protein executed five different activities in a solution, such as reacting to antibodies and changing intestinal acidity. "It's a nice tool in our toolbox," says the study's senior author Alexis Vallée-Bélisle, a nanotechnology researcher at the Université de Montréal.

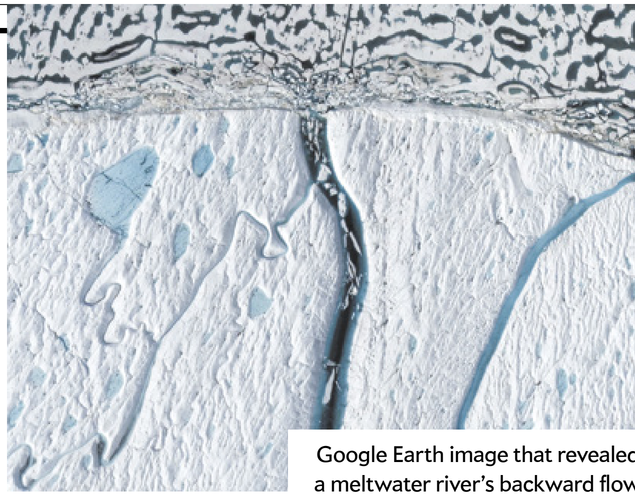


Other researchers have built nanoantennas from metals that attach to any protein encountered. But the new antennas' DNA-based structure can be programmed to adhere to a specific protein—or region on a protein—based on a sequence of building blocks called nucleotides. "They're like Legos," says Mina Yeşilyurt, a physicist at the Leibniz Institute of Photonic Technology who was not involved in the study. "You can create endless combinations."

Sensing structural changes in specific molecules has big implications for drug development, the study authors say. Vallée-Bélisle uses the example of a protein involved in turning cells cancerous. Researchers could introduce fluorescent nanoantennas to monitor whether a drug successfully blocks the cancer-causing protein from binding to a healthy cell analogue in the lab.

Fluorescent nanoantennas are still subject to many of the same limitations as older techniques, such as false positives that arise when proteins unfold because of interference from the antennas themselves. "There is no silver bullet that solves all of the problems in these things," says Ahmet Ali Yanik, a nanoplasmonics engineer at the University of California, Santa Cruz, who was not involved with the research.

But Yanik does think the approach will be useful—especially given its relative affordability compared with other ways of monitoring proteins, such as x-ray crystallography. "Every biology lab has a fluorescence microscope," he says. "So it's definitely a technique that can catch on." *—Joanna Thompson*



Google Earth image that revealed a meltwater river's backward flow

GLACIOLOGY

Rivers of Trouble

River reversals destabilize ice shelves

Columbia University glaciologist Alexandra Boghosian spent two years studying a meltwater river on Greenland's Petermann Ice Shelf. She suspected the river ended in a waterfall like the one that cascades off the Nansen Ice Shelf in Antarctica, potentially keeping water from accumulating in melt ponds that can damage the ice. Instead Boghosian and her team discovered a new phenomenon: a deep-cut river channel that could contribute to future ice-calving events and accelerate sea-level rise.

The team first spotted the phenomenon in 2018 using Google Earth; an overhead view showed sea ice floating in a river carving into the ice shelf. Further work confirmed this river had cut so deep its water actually flowed backward, from the sea up to half a mile into the channel. "We called it an 'estuary' because of the evidence of this flow reversal that mixes fresh and salt water," Boghosian says. She and her colleagues detailed their find in *Nature Geoscience*.

The researchers also noticed ice fractures running parallel to the river along its backward-flowing section. "The type of fractures they found can really set up ice for failure because ocean water can get in there and erode them," says Catherine Walker, a glaciologist at the Woods Hole Oceanographic Institution, who was not involved with the study. Such fractures can contribute to calving events, in which large blocks crack off a shelf. With reduced mass, shelves cannot as readily hold back advancing glaciers behind them, and more ice flows into the ocean, raising sea levels faster. Increasing temperatures from climate change could cause more of these rivers to run for longer periods with more meltwater and cut too deep.

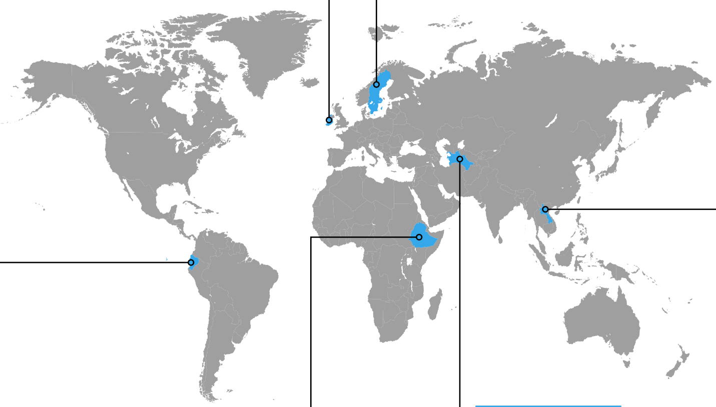
Relatively warm water flows in "upside-down rivers" underneath some ice shelves, melting the bottom and letting surface ice settle to form depressions on top. Water flowing through such channels could also make shelves more prone to forming estuaries. "These linear features mean the river is going to form in the same place every year, allowing the water to incise deeper," Boghosian says.

Most of the world's ice shelves are in Antarctica and experience less meltwater than Greenland's do, but climate change could lessen the gap. "I don't think the volume of meltwater has been able to establish one of these estuaries in Antarctica," Walker says, "but this study is certainly forward-looking as to what could happen to weaken those big ice shelves." *—Theo Nicitopoulos*

Google Earth

Illustration by Thomas Fuchs

IN THE NEWS
Quick Hits
By Joanna Thompson



IRELAND
Archaeologists unearthed evidence of at least 58 Neolithic cattle in northern Dublin. Each animal was slaughtered at peak age for meat production, suggesting the site was host to massive communal barbecues.

SWEDEN
New Caledonian crows are learning to clean up litter. A pilot program launched in Stockholm by start-up Corvid Cleaning uses food-dispensing robots to train the brainy birds to pick up cigarette butts.

ECUADOR
New fishing restrictions covering 20,000 square miles around the Galápagos Islands aim to create an underwater "highway" for local wildlife. This region would help link neighboring countries' protected areas along the Pacific coast.

LAOS
The World Wildlife Fund described an astonishing 224 newly documented species in a region encompassing parts of Laos, Vietnam, Cambodia, Thailand and Myanmar. These finds include a slug-eating snake, a monkey with white-ringed eyes and the first-ever succulent bamboo, which is found only in Laos.

ETHIOPIA
Paleoanthropologists analyzed crystals in a layer of volcanic ash to reevaluate the age of Kibish Omo I, a fossil that is among Earth's oldest human remains. The specimen appears to be 233,000 years old—more than 30,000 years older than previously thought.

TURKMENISTAN
President Gurbanguly Berdymukhammedov has set up a committee tasked with closing the "Gates of Hell," a 230-foot-wide crater that has been engulfed in flames for more than 50 years. The crater, the site of a former Soviet gas-mining operation, was intentionally set ablaze in 1971.

For more details, visit www.ScientificAmerican.com/apr2022/advances

BIOLOGY

Science in Images

By Leslie Nemo

When Barry Webb is crawling around on the forest floor with a flashlight, passersby understandably give him strange looks. The U.K.-based photographer is hunting for something others might struggle to see: slime mold growths that stand less than a tenth of an inch high.

For scientists, classifying slime molds has proved as slippery as the name suggests. These life-forms have previously been labeled plants, fungi and even animals, but they are actually lesser-known organisms called protists. Slime molds coat wet and decaying surfaces, including dead trees, leaf litter and dung, often functioning as a single cell with many nuclei. Just before dying, they send up fruiting bodies to reproduce, which Webb catches on camera.

Each of Webb's images consists of 30 to 100 photographs taken with different focal points. When assembled, the composite shows more detail than any one snapshot could. Most specimens Webb captures are in the woods near his home in England's Buckinghamshire County, but some grow on decaying logs he keeps in his garden to see what might emerge. If you would like to try something similar, it is easy to do—just beware of hungry slugs, Webb warns.

1. *Comatricha nigra* grows on a fallen beech log just before releasing its spores. Many slime molds, including those in this genus, find the perfect place to settle down by scooting around via pseudopods—cellular extensions that shoot forward for the rest of the cell to coalesce around.

2. *Metatrichia floriformis's* sprouted casings crack open as they dry out, allowing wind to lift away spores that eventually form into amoebalike creatures. These organisms can harden into a stationary cyst or grow a "tail" and move around, depending on how wet their final destination is.

3. *Cribraria aurantiaca* produces vivid fruiting bodies. Slime molds such as *C. aurantiaca* always occupy new patches of wet logs or other surfaces; they leave residue behind as they move and avoid places already streaked with their goo.

4. *Physarum leucophaeum* line the edge of a beech leaf. These slime molds are impressive problem solvers. Researchers have plopped other members of the genus *Physarum* into mazes and watched them find the shortest path through. *Physarum* has even inspired a slime mold algorithm that researchers deployed to map filaments of dark matter connecting galaxies throughout the universe.

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Barry Webb (*all images*)

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CHEMISTRY

Power Up

New technique puts crumbling batteries back together

For electric cars to run as long as possible between charges, their batteries need to pack a punch. One option would be lithium-metal batteries, which have a key component made of this lightweight element. This gives them greater storage capacity than widely used lithium-ion batteries, with the same component made from graphite. Although lithium-metal batteries can store more energy than lithium-ion batteries of the same size, they also degrade faster, limiting how many times they can charge and discharge. But researchers have found a new charging technique that can actually restore the damaged material, significantly extending the battery's lifetime.

As a rechargeable lithium-based battery charges and discharges, lithium ions move back and forth between the positively charged cathode and the negatively charged anode. But over time, small pieces of the reactive material fail to latch onto the anode's body. Within the battery, the lost chunks form tiny lithium "islands" that most researchers had considered inactive—until now. Stanford University researchers found that these isolated bits could still respond electrically, physically moving back and forth as the battery charged and discharged. Their discovery was published in *Nature*.

The scientists found that the islands could wiggle around enough to reestablish an electrical connection between the isolated lithium and the anode. They realized they could coax the material back together by immediately discharging a small amount of electricity after the battery had been charged to capacity. "That's how we promote [the lost lithium's] growth toward the anode to reestablish the electrical connection," says the study's lead author and Stanford materials scientist Fang Liu. When a lithium-metal test battery was charged using this protocol, it could perform more charging cycles, lasting 29 percent longer than a battery that underwent standard charging.

Kelsey Hatzell, a Princeton University electrochemical and materials scientist who was not involved in the study, says the finding contributes to the fundamental understanding of lithium-metal batteries. "Observing … the dynamics of isolated lithium metal is very challenging," she says, adding that the researchers "have designed a lot of very intriguing experiments to start to deconvolute the mechanisms." She notes, however, that practical applications may be far off; these batteries still fall short of the thousands of charging cycles that rechargeable batteries must endure.

The Stanford researchers hope to further develop their charging method to maximize lithium-metal battery lifetime. They are also working on a charging protocol that would extend lithium-ion batteries' usability. "I will consider [this study] as a major discovery for the battery field—lithium-ion, lithium-metal," says senior author and Stanford materials scientist Yi Cui. "It can be generalized, I think, to the whole battery field."

—Sophie Bushwick

BIOLOGY

Sheathed Blades

Subtle tweaks to common genetic patterns explain key grass leaf structure

Picture a clump of grass—a spray of flat green blades that converge into sturdy tubes near the ground. These tubes are formed by the curled lower portion of the grass leaf, called the sheath, which represents something of an evolutionary triumph. It allows grass to grow from the base (instead of the stem, like most other flowering plants) by protecting new growth and holding mature blades upright so they can compete for sunlight. This growth strategy helps to explain why lawns survive mowing and how grasslands dominate more than a quarter of Earth's land area: by tolerating grazing and wildfires better than stem-growing competitors.

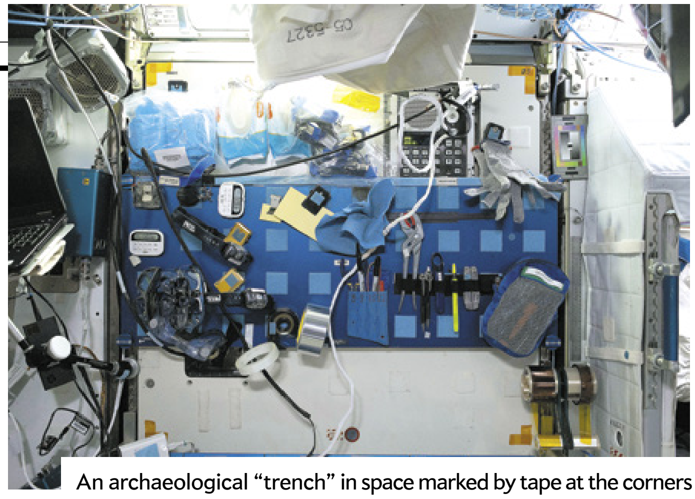
Scientists have long debated the evolutionary origins of the sheath, which is found in all grasses, including corn, wheat and bamboo. Now a new study in *Science* illustrates how the novel structure of the grass leaf arose from the same genetic pattern that governs other plants' leaf development. "It's not that we got new things bolted on and added," says the study's lead author Annis Richardson, a developmental geneticist at the University of Edinburgh. "The connections were tweaked."

Richardson and her colleagues started by taking 3-D images of corn seedlings as they matured, then re-creating the plant's development using a computer model. The researchers honed their model further by comparing it with experimental observations, such as where certain genes activate in plants and how genetic mutations affect leaf shape. Then they turned to the sheath.

In the 1800s botanists proposed that the sheath part of a grass leaf represented the evolutionary equivalent of the petiole, the stalk that connects a typical plant's leaf to its stem. Later, many scientists concluded based on vein patterns that beyond just the sheath, the entire grass leaf—or most of it—actually corresponded to this stalk. Richardson and her team tested both hypotheses in their model and found that the older idea, linking only the sheath to the petiole, offered the simplest evolutionary path and required only subtle changes in a common genetic blueprint.

Aman Husbands, a developmental biologist at the University of Pennsylvania who was not involved in the study, says the researchers tied together clues about the sheath from other leaf studies and "put it all together into a model that actually explains it and really settles it."

An improved understanding of what controls leaf shape could help scientists engineer better crops, Richardson says. Identifying the sheath's origin also sheds light on grass evolution. Although grass's unique structure had enormous consequences for Earth's landscapes and inhabitants—including humans, who get more than half their calories from domesticated grass grains—she adds, "we now understand that that leaf shape wasn't that hard to develop." —*Julia Rosen*



An archaeological "trench" in space marked by tape at the corners

NASA and International Space Station Archaeological Project

ARCHAEOLOGY

One Small Step

Space station archaeology digs into astronaut culture

NASA astronaut Kayla Barron floated into an International Space Station module in January with a roll of yellow tape and an unusual assignment: setting up the first of six "trenches" for an archaeological investigation.

Back on Earth, archaeologists Alice Gorman of Flinders University in Australia and Justin Walsh of Chapman University in California watched and offered feedback. They had previously mined existing video footage to study astronaut culture, but their Sampling Quadrangle Assemblages Research Experiment, dubbed SQuARE, marks the first real off-world "dig."

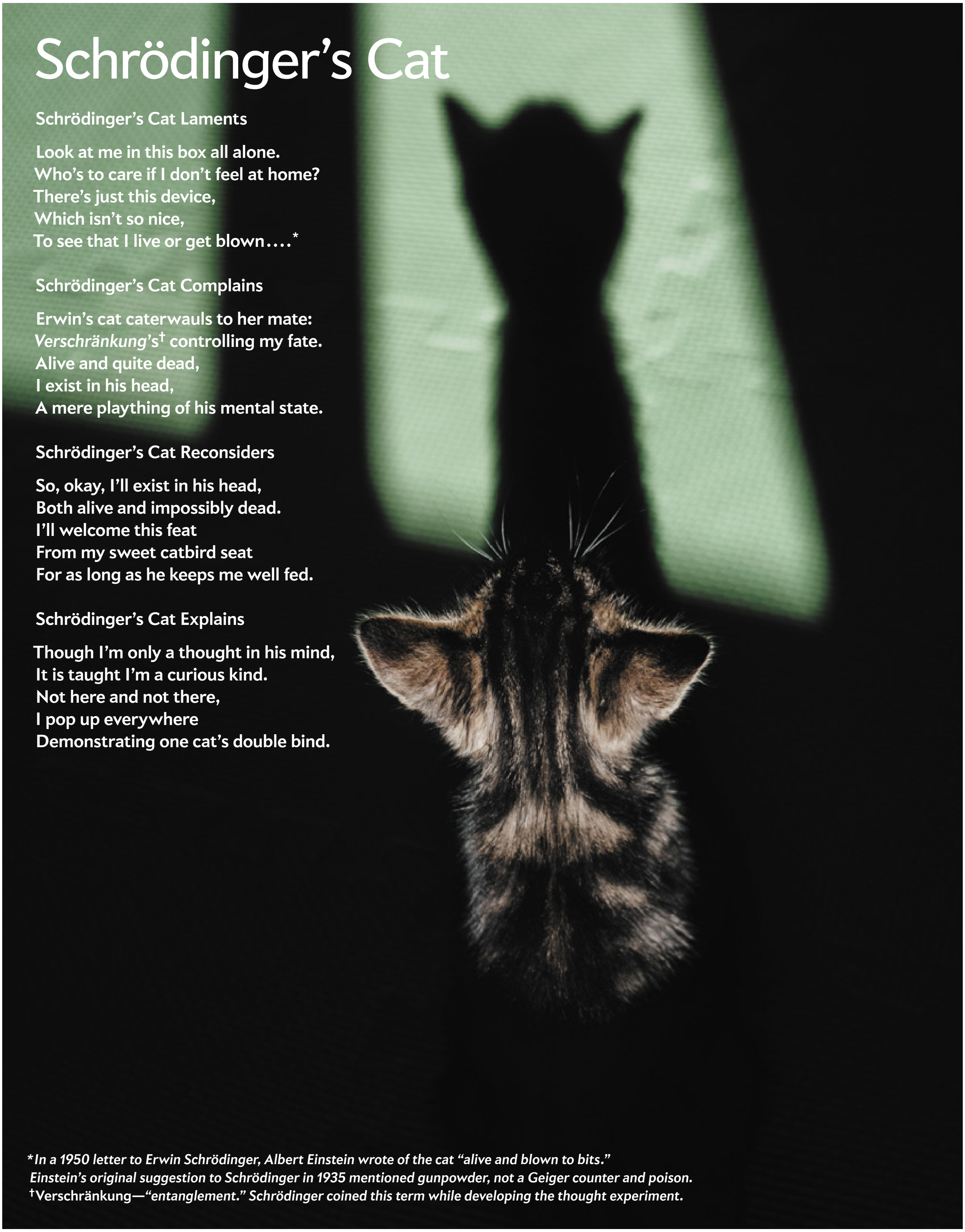
In terrestrial archaeology, researchers often record every bone, pottery fragment and stone tool found in small, well-defined trenches. Adapting that well-honed methodology, SQuARE had astronauts take daily photographs of one-meter squares marked off by tape. The researchers back on Earth then documented all objects entering and exiting those six spots over 60 days, until the work wrapped up in March. "Every image is like a layer of soil that we're removing, revealing a new period and a new set of activities that have happened in that area," Walsh says. The sampled areas included a workstation, a galley and the wall across from the U.S. toilet. These trenches were full of artifacts, including scissors, wrenches, pens, condiments and one of Gorman's obsessions: Ziploc bags.

"Lots of people think of archaeology as gold masks and pyramids and sculptures and things like that," Gorman says—not the utensils, pots and other objects more often studied. "That's the really fascinating stuff." Amid the expensive, highly designed and irreplaceable components often found in spacecraft, mass-produced plastic bags affixed to surfaces are crucial as a form of what Gorman calls "portable gravity," along with Velcro, cable ties, handholds and footholds that help items (and people) stay in place.

Better data on such artifacts' use could influence future space habitat design. And SQuARE has a historic preservation component, too: the more than 20-year-old station is set to be decommissioned in 2030. "It's really the direction that space archaeology should go," says anthropologist Beth O'Leary, a pioneer in this burgeoning field and professor emerita at New Mexico State University, who was not involved in the study. SQuARE data could illuminate how astronauts create subcultures in space, she adds.

In earlier work, the team showed how Russian cosmonauts over several decades and multiple space stations informally passed down a way of using empty wall space to create shrines honoring heroes such as astronaut Yuri Gagarin. "There seems to have been a transmission of what to do," Walsh says, "which is what culture is—it's these traditional practices that get developed, then reinforced and transformed." —*Megan I. Gannon*

Peggy Landsman is a widely published and widely traveled poet who has taught English in the U.S., China, Japan and Hungary. Her two chapbooks are *Our Words, Our Worlds* (2021) and *To-wit To-woo* (2008). Read more at peggylandsman.wordpress.com



Schrödinger's Cat

Schrödinger's Cat Laments

Look at me in this box all alone.
Who's to care if I don't feel at home?
There's just this device,
Which isn't so nice,
To see that I live or get blown. . . .*

Schrödinger's Cat Complains

Erwin's cat caterwauls to her mate:
Verschränkung's† controlling my fate.
Alive and quite dead,
I exist in his head,
A mere plaything of his mental state.

Schrödinger's Cat Reconsiders

So, okay, I'll exist in his head,
Both alive and impossibly dead.
I'll welcome this feat
From my sweet catbird seat
For as long as he keeps me well fed.

Schrödinger's Cat Explains

Though I'm only a thought in his mind,
It is taught I'm a curious kind.
Not here and not there,
I pop up everywhere
Demonstrating one cat's double bind.

**In a 1950 letter to Erwin Schrödinger, Albert Einstein wrote of the cat "alive and blown to bits." Einstein's original suggestion to Schrödinger in 1935 mentioned gunpowder, not a Geiger counter and poison.*
†Verschränkung—"entanglement." Schrödinger coined this term while developing the thought experiment.

Ana Rocio Garcia Franco/Getty Images

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.*

Better Local Cancer Care

Community oncologists get help keeping up with a torrent of new treatments

By Claudia Wallis

New treatments for cancer are being developed at a breathtaking pace. Novel drugs, immunotherapies that enhance the body's ability to attack tumors, and other innovations have been approved at a rate of three or four a month. "Ten years ago it was 10 a year; today the pace is one a week," marvels oncologist Tufia Haddad, a breast cancer specialist at the Mayo Clinic. These therapies are not the decisive triumphs in the "war on cancer" that politicians have promised since the 1970s. But they are smaller wins, including the first treatments focused on the specific biology of small-cell lung cancer, metastatic melanoma and aggressive "triple-negative" breast cancer.

Many of the therapeutics target a gene mutation or protein and are paired with diagnostic tests that probe tumor cells or blood for these "biomarkers." The influx of so many new tools poses both an opportunity and a challenge. Just keeping up with breast cancer is not easy, Haddad says: "My heart goes out to community oncologists who are taking care of all cancer patients."

Community oncologists—as opposed to subspecialists working at top cancer centers—provide about 80 percent of cancer care in the U.S., treating a wide variety of malignancies. "On any given day they might see 30 different patients with 30 different diagnoses," says hematologist Joseph Alvarnas of the City of Hope Comprehensive Cancer Center in Duarte, Calif. "Incorporating this torrential evolution of knowledge is an impossible, Sisyphean task."

The information deluge is compounded by logistical obstacles. Some of the biomarker tests have to be handled by specialized laboratories, which can make them hard to access, says oncologist Arif Kamal of Duke University. The drugs themselves can have stratospheric costs, and insurance companies may delay authorization or require that patients try a cheaper drug first. Major cancer centers have the resources to work around such barriers and to offer patients greater access to clinical trials, which provide the latest treatments for free. No one doubts that community oncologists want the very best for their patients, but to make the newest therapies more available—particularly to rural populations and underserved communities of color—physicians may need strong partnerships with big cancer centers and smarter technology.

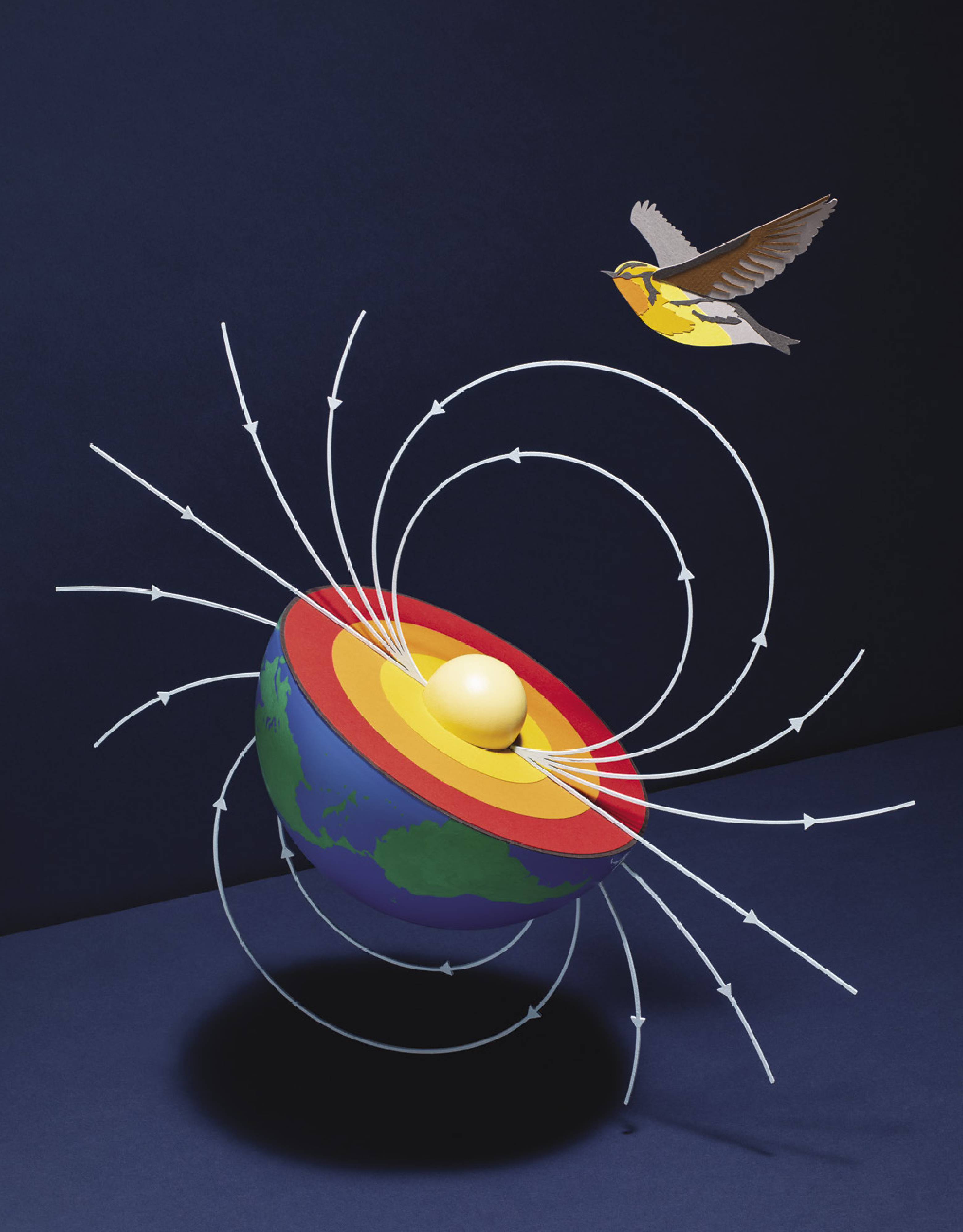
Two key avenues for spreading knowledge are through the National Cancer Institute's PDQ Web site and guidelines maintained by the National Comprehensive Cancer Network, an alliance of 31 leading U.S. cancer centers. Expertise also expands through partnerships between oncologists at smaller practices and comprehensive cancer centers. City of Hope, for example, together with three other centers, contracts with businesses to provide cancer care to their employees through a service called AccessHope. It pairs far-flung doctors with cancer center oncologists. "We are able to look at the most complex patients at the time of initial therapy decision-making or time of relapse," Alvarnas explains, "and we remain a phone call away as things change for that patient." A 2021 study led by Alvarnas's colleague Howard West found that in 28 percent of lung cancer cases, AccessHope experts recommended a different course of treatment than what was locally provided.

Ties to top cancer centers can also make it easier for community oncologists to enroll their patients in clinical trials. Surgical oncologist Monica Bertagnolli of Boston's Dana-Farber Cancer Institute notes that half of the 117 sites in the Alliance for Clinical Trials in Oncology, which she chairs, are community practices, including single-doctor offices. "Doctors who do research are not only up on what's current; they are also trying to develop new treatments."

The difference made by the latest therapies can vary. For people with metastatic melanoma, they have raised the five-year survival rate from 10 to 50 percent. Even when a new drug provides just a two-month edge in median survival, Bertagnolli notes, "if it's a new treatment pathway, you may be able to combine it with something else that makes a bigger difference."

Many experts foresee a day when artificial intelligence will help guide such clinical decisions. "Ultimately we may be able to apply machine learning to the data in electronic health records, which should include all the biomarkers, pathology and characteristics of the patient," says William Cance, scientific director of the American Cancer Society. But there is a long way to go because health-record systems are optimized for billing, not for tracking outcomes. Bertagnolli, a self-described "small-town girl from Wyoming," says the community doctors in her research alliance are already working to improve those systems: "These people are my heroes." SA

Illustration by Fatinha Ramos



Peter J. Hore is a chemist at the University of Oxford. He works on the biophysical chemistry of electron and nuclear spins and their effects on processes such as the mechanisms of animal magnetoreception.

Henrik Mouritsen is a biologist at the University of Oldenburg in Germany. He studies the mechanisms of orientation and navigation in many different animals with an emphasis on night-migrating songbirds.

BIOPHYSICAL CHEMISTRY

The Quantum Nature of Bird Migration

Migratory birds travel vast distances between their breeding and wintering grounds. New research hints at the biophysical underpinnings of their internal navigation system

By Peter J. Hore and Henrik Mouritsen

Illustration by Kyle Bean

IMAGINE YOU ARE A YOUNG BAR-TAILED GODWIT, A LARGE, LEGGY SHOREBIRD WITH A LONG, PROBING bill hatched on the tundra of Alaska. As the days become shorter and the icy winter looms, you feel the urge to embark on one of the most impressive migrations on Earth: a nonstop trans-equatorial flight lasting at least seven days and nights across the Pacific Ocean to New Zealand 12,000 kilometers away. It's do or die. Every year tens of thousands of Bar-tailed Godwits complete this journey successfully. Billions of other young birds, including warblers and flycatchers, terns and sandpipers, set out on similarly spectacular and dangerous migrations every spring, skillfully navigating the night skies without any help from more experienced birds.

People have long puzzled over the seasonal appearances and disappearances of birds. Aristotle thought that some birds such as swallows hibernated in the colder months and that others transformed into different species—redstarts turned into robins for the winter, he proposed. Only in the past century or so, with the advent of bird banding, satellite tracking and more widespread field studies, have researchers been able to connect bird populations that winter in one area and nest in another and show that some travel vast distances between the two locales every year. Remarkably, even juvenile long-haul travelers know where to go, and birds often take the same routes year after year. How do they find their way?

Migrating birds use celestial cues to navigate, much as sailors of yore used the sun and stars to guide them. But unlike humans, birds also detect the magnetic field generated by Earth's molten core and use it to determine their position and direction. Despite more than 50 years of research into magnetoreception in birds, scientists have been unable to work out exactly how they use this information to stay on course. Recently we and others have made inroads into this enduring mystery. Our experimental evidence suggests something extraordinary: a bird's compass relies on subtle, fundamentally quantum effects in short-lived molecular fragments, known as radical pairs, formed photochemically in its eyes. That is, the creatures appear to be able to "see" Earth's magnetic field lines and use that information to chart a course between their breeding and wintering grounds.

A MYSTERIOUS SENSE

MIGRATORY BIRDS have an internal clock with an annual rhythm that tells them, among other things, when to migrate. They also inherit from their parents the directions in which they need to fly in the autumn and spring, and if the parents each have different genetically encoded directions, their offspring will end up with an intermediate direction. For example, if a southwest-migrating bird is crossed with a southeast-migrating bird, their offspring will head south when the time comes. But how do the young birds know which direction is southwest or south or southeast? They have at least three different compasses at their disposal: one allows them to extract information from the position of the sun in the sky, another uses the patterns of the stars at night, and the third is based on Earth's ever present magnetic field.

In their first autumn, young birds follow inherited instructions such as "fly southwest for three weeks and then south-southeast for two weeks." If they make a mistake or are blown off course, they are generally unable to recover because they do not yet have a functioning map that would tell them where they are. This is one of the reasons why only 30 percent of small songbirds survive their first migrations to their wintering grounds and back again. During its first migration a bird builds up a map in its brain that, on subsequent journeys, will enable it to navigate with an ultimate precision of centimeters over thousands of kilometers. Some birds breed in the same nest box and sleep on the same perch in their wintering range year after year. Equipped with this map, about 50 percent of adult songbirds make it back to their nesting site to breed every year.

Migratory birds' navigational input comes from several senses—mainly sight, smell and magnetoreception. By observing the apparent nighttime rotation of the stars around the North Star, the birds learn to locate north before they embark on their first migration, and an internal 24-hour clock allows them to calibrate their sun compass. Characteristic smells can help birds recognize places they have visited before. Scientists know a great deal about the detailed biophysical mechanisms of the birds' senses of sight and smell. But the inner workings of their magnetic compass have proved harder to understand.

The magnetic direction sense in small songbirds that migrate at night is remarkable in several important respects. First, observations of caged birds exposed to carefully controlled magnetic fields show that their compass does not behave like the magnetized needle in a ship's compass. A bird detects the axis of the magnetic field and the angle it makes with Earth's surface, the so-called inclination compass. In laboratory experiments, inverting the magnetic field's direction so that it points in exactly the opposite direction has no effect on the bird's ability to orient correctly. Second, a bird's perception of Earth's magnetic field can be disrupted by extraordinarily weak magnetic fields that reverse their direction several million times per second. Last, even though songbirds fly at night under the dim light of the stars, their magnetic compass is light-dependent, hinting at a link between vision and magnetic sensing.

In 1978, in an attempt to make sense of these features of avian magnetoreception, Klaus Schulten, then at the Max Planck Institute for Biophysical Chemistry in Göttingen, Germany, put forth a remarkable idea: that the compass relies on magnetically sensitive chemical transformations. At first glance, this proposal seems preposterous because the energy available from Earth's magnetic field is millions of times too small to break, or even significantly weaken, the bonds between atoms in molecules. But Schulten was inspired by the discovery 10 years previously that short-lived chemical intermediates known as radical pairs have unique properties that make their chemistry sensitive to feeble magnetic interactions. Over the past 40 years researchers have conducted hundreds of lab studies of radical-pair reactions that are affected by the application of magnetic fields.

To appreciate why radical pairs are so special, we need to talk about a quantum-mechanical property of the electron known as spin angular momentum, or "spin" for short. Spin is a vector with a direction as well as a magnitude, and it is often represented by an arrow, ↑ or ↓, for example. Particles with spin have magnetic moments, which is to say they behave like microscopic magnets. Most molecules have an even number of electrons arranged in pairs with opposed spins (↑↓), which therefore cancel each other out. Radicals are molecules that have lost or gained an electron, meaning that they contain an odd, unpaired, electron and hence have a spin and a magnetic moment. When two radicals are created simultaneously by a chemical reaction (this is what we mean by radical pair), the two unpaired electrons, one in each radical, can have either antiparallel spins (↑↓) or parallel spins (↑↑), arrangements known as singlet and triplet states, respectively.

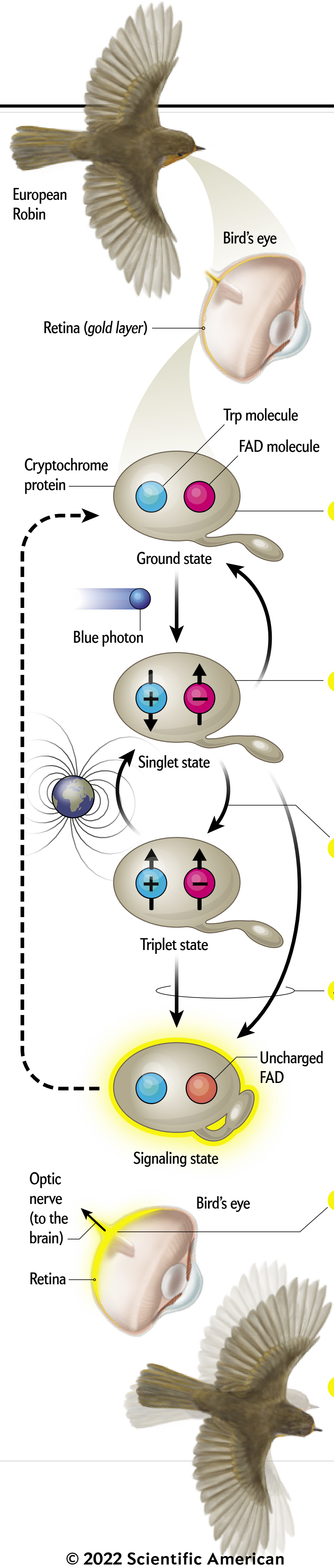
Immediately after a radical pair is created in a singlet state, internal magnetic fields cause the two electronic spins to undergo a complex quantum "waltz" in which singlet turns into triplet and triplet turns back into singlet millions of times per second for periods of up to a few microseconds. Crucially, under the right conditions, this dance can be influenced by external magnetic fields. Schulten suggested that this subtle quantum effect could form the basis of a magnetic compass sense that might respond to environmental stimuli a million times weaker than would normally be thought possible. Research that we and others have carried out in recent years has generated fresh support for this hypothesis.

A POSSIBLE MECHANISM

TO BE USEFUL, hypotheses need to explain known facts and make testable predictions. Two aspects of Schulten's proposed compass mechanism are consistent with what is known about the birds' compass: radical pairs are indifferent to exact external magnetic field reversals, and radical pairs are often formed when molecules absorb light. Given that the birds' magnetic compass is light-dependent, a prediction of Schulten's

The Compass Mechanism

Studies suggest that the magnetic compass of migratory birds relies on quantum effects in short-lived molecular fragments known as radical pairs that are formed photochemically in the eyes. In this way, the birds can perceive Earth's magnetic field lines and use that information to navigate their long-haul trips.



1 Cryptochrome proteins—located in the retinal cells of the bird's eye—include a flavin adenine dinucleotide molecule (FAD) and a tryptophan amino acid (Trp). In the stable state, these molecules are electrically neutral, and a small section of the protein probably extends like a tail.

2 When a photon of blue light hits the cryptochrome, an electron jumps from the Trp onto the FAD. The resulting molecules—each with an odd number of electrons—are known as a radical pair. In this singlet state, the molecules' unpaired electrons spin in opposition.

3 The activated protein oscillates rapidly back and forth between the singlet state and the triplet state, in which the unpaired electrons spin in parallel. Earth's magnetic field influences the spin, impacting the likelihood of each state dominating.

4 Both states can undergo chemical reactions that transform them into the "signaling state"—in which a hydrogen ion has been added to the FAD radical—and the tail seems to move closer to the body of the protein. The singlet state can also simply return to the ground state. The proportion of outcomes depends on the bird's orientation in Earth's magnetic field.

5 The signaling state of the cryptochrome turns on a biochemical cascade that triggers the release of neurotransmitter molecules in the retina. Signals continue to the bird's brain, where the magnetic information they contain is integrated with information from other directional cues, informing the direction of the bird's flight.

6 Cryptochrome returns to its ground state, and the process starts again (*dashed arrow*).

Graphic by Jillian Ditner (birds and eyes) and Jen Christiansen hypothesis is that their eyes play a part in the magnetic sensory system. About 10 years ago the research group of one of us (Mouritsen) at the University of Oldenburg in Germany found that a brain region called Cluster N, which receives and processes visual information, is by far the most active part of the brain when certain night-migrating birds are using their magnetic compass. If Cluster N is dysfunctional, research in migratory European Robins showed, the birds can still use their sun and star compasses, but they are incapable of orienting using Earth's magnetic field. From experiments such as these, it is clear that the magnetic compass sensors are located in the birds' retinas.

One early objection to the radical-pair hypothesis was that no one had ever shown that magnetic fields as tiny as Earth's, which are 10 to 100 times weaker than a fridge magnet, could affect a chemical reaction. To address this point, Christiane Timmel of the University of Oxford and her colleagues chose a molecule chemically unlike anything one would find inside a bird: one that contained an electron donor molecule linked to an electron acceptor molecule via a molecular bridge. Exposing the molecules to green light caused an electron to jump from the donor to the acceptor over a distance of about four nanometers. The radical pair that formed from this reaction was extremely sensitive to weak magnetic interactions, proving that it is indeed possible for a radical-pair reaction to be influenced by the presence of—and, more important, the direction of—an Earth-strength magnetic field.

EUROPEAN ROBIN (*top*) and Bar-tailed Godwit (*bottom*) are among the many birds that migrate long distances.

Adrian Coleman/Getty Images; Imogen Warren/Getty Images (*top and bottom*)

Schulten's hypothesis also predicts that there must be sensory molecules (magnetoreceptors) in the retina in which magnetically sensitive radical pairs can be created using the wavelengths birds need for their compass to operate, which another line of research had identified as light centered in the blue region of the spectrum. In 2000 he suggested that the necessary photochemistry could take place in a then recently discovered protein called cryptochrome.

Cryptochromes are found in plants, insects, fish, birds and humans. They have a variety of functions, including light-dependent control of plant growth and regulation of circadian clocks. What makes them attractive as potential compass sensors is that they are the only known naturally occurring photoreceptors in any vertebrate that form radical pairs when they absorb blue light. Six types of cryptochromes have been found in the eyes of migratory birds, and no other type of candidate magnetoreceptor molecule has emerged in the past 20 years.

Like all other proteins, cryptochromes are composed of chains of amino acids folded up into complex three-dimensional structures. Buried deep in the center of many cryptochromes is a yellow molecule called flavin adenine dinucleotide (FAD) that, unlike the rest of the protein, absorbs blue light. Embedded among the 500 or so amino acids that make up a typical cryptochrome is a roughly linear chain of three or four tryptophan amino acids stretching from the FAD out to the surface of the protein. Immediately after the FAD absorbs a blue photon, an electron from the nearest tryptophan hops onto the flavin portion of the FAD. The first tryptophan then attracts an electron from the second tryptophan and so on. In this way, the tryptophan chain behaves like a molecular wire. The net result is a radical pair made of a negatively charged FAD radical in the center of the protein and, two nanometers away, a positively charged tryptophan radical at the surface of the protein.

In 2012 one of us (Hore), working with colleagues at Oxford, carried out experiments to test the suitability of cryptochrome as a magnetic sensor. The study used cryptochrome-1, a protein found in *Arabidopsis thaliana,* the plant in which cryptochromes had been discovered 20 years earlier. Using short laser pulses to produce radical pairs inside the purified proteins, we found that we could fine-tune their subsequent reactions by applying magnetic fields. This was all very encouraging, but, of course, plants don't migrate.

We had to wait almost a decade before we could make similar measurements on a cryptochrome from a migratory bird. The first challenge was to decide which of the six bird cryptochromes to look at. We chose cryptochrome-4a (Cry4a), partly because it binds FAD much more strongly than do some of its siblings, and if there is no FAD in the protein, there will be no radical pairs and no magnetic sensitivity. Experiments in Oldenburg also showed that the levels of Cry4a in migratory birds are higher during the spring and autumn migratory seasons than they are during winter and summer when the birds do not migrate. Computer simulations performed by Ilia Solov'yov in Oldenburg showed that European Robin Cry4a has a chain of four tryptophans—one more than the Cry1 from *Arabidopsis*. Naturally, we wondered whether the extended chain had evolved to optimize magnetic sensing in migratory birds.

Our next challenge was to get large amounts of highly pure robin Cry4a. Jingjing Xu, a Ph.D. student in Mouritsen's lab, solved it. After optimizing the experimental conditions, she was able to use bacterial cell cultures to produce samples of the protein with the FAD correctly bound. She also prepared versions of the protein in which each of the four tryptophans was replaced, one at a time, by a different amino acid so as to block electron hopping at each of the four positions along the chain. Working with these alternative versions of the protein would allow us to test whether the electrons are really jumping all the way along the tryptophan chain.

We shipped these samples—the first purified cryptochromes from any migratory animal—to Oxford, where Timmel and her husband, Stuart Mackenzie, studied them using the sensitive laser-based techniques they had developed specifically for that purpose. Their research groups found that both the third and fourth tryptophan radicals at the end of the chain are magnetically sensitive when paired with the FAD radical. We suspect that the tryptophans work cooperatively for efficient magnetic sensing, biochemical signaling and direction finding. We also speculate that the presence of the fourth tryptophan might enhance the initial steps of signal transduction, the process by which nerve impulses encoding the magnetic field direction are generated and ultimately sent along the optic nerve to the brain. We are currently conducting experiments to identify the proteins that interact with Cry4a.

One more cryptochrome finding deserves mention here. We compared robin Cry4a with the extremely similar Cry4a proteins from two nonmigratory birds, pigeons and chickens. The robin protein had the largest magnetic sensitivity, hinting that evolution might have optimized robin Cry4a for navigation.

OPEN QUESTIONS

ALTHOUGH THESE EXPERIMENTS confirm that Cry4a has some of the properties required of a magnetoreceptor, we are still a long way from proving how migratory birds perceive Earth's magnetic field lines. One crucial next step is to determine whether radical pairs actually form in the eyes of migratory birds.

The most promising way to test for radical pairs inside the birds' eyes was inspired by the work of chemists and physicists who, in the 1980s, showed that fluctuating magnetic fields alter the way radical-pair reactions respond to static magnetic fields. Their work predicted that a weak radio-frequency electromagnetic field, fluctuating with the same frequencies as the "singlet-triplet waltz," might interfere with the birds' ability to use their magnetic compass. Thorsten Ritz of the University of California, Irvine, and his colleagues were the first to confirm this prediction in 2004.

In 2007 Mouritsen began similar behavioral experiments in his lab in Oldenburg—with intriguingly different results. During the spring and fall, birds that travel between nesting and wintering grounds exhibit a behavior called *Zugunruhe,* or migratory restlessness, as if they are anxious to get on their way. When caged, these birds usually use their magnetic compass to instinctively orient themselves in the direction in which they would fly in the wild. Mouritsen found that European Robins tested in wooden huts on his university's campus were unable to orient using their magnetic compass. He suspected that weak radio-frequency noise (sometimes called electrosmog) generated by electrical equipment in the nearby labs was interfering with the birds' magnetic compass.

To confirm that electrosmog was the source of the problem, Mouritsen and his team lined the huts with aluminum sheets to block the stray radio frequencies. On nights when the shields were grounded and functioned properly, the birds oriented well in Earth's magnetic field. On nights when the grounding was disconnected, the birds jumped in random directions. When tested in an unshielded wooden shelter typically used for horses some kilometers outside the city and well away from electrical equipment, the same birds had no trouble detecting the direction of the magnetic field.

These results are significant on several fronts. If the radio-frequency fields affect the magnetic sensor and not, say, some component of the signaling pathway that carries nerve impulses to the brain, then they provide compelling evidence that a radical-pair mechanism underpins the bird's magnetic compass. The main competing hypothesis, for which there is currently much less support, proposes that magnetic iron–containing minerals are the sensors. Any such particles that were large enough to align like a compass needle in Earth's magnetic field would be far too big to rotate in a much weaker field that reversed its direction millions of times per second. Furthermore, the radio-frequency fields that upset the birds' magnetic orientation are astonishingly weak, and we don't yet understand exactly how they could corrupt the directional information available from the much stronger magnetic field of Earth.

It is also remarkable that the birds in the Oldenburg lab were disoriented much more effectively by broadband radio-frequency noise (randomly fluctuating magnetic fields with a range of frequencies) than by the single-frequency fields mostly used by Ritz and his collaborators. We hope that by subjecting migratory songbirds to bands of radio-frequency noise with different frequencies we will be able to determine whether the sensors really are FAD-tryptophan radical pairs or whether, as some other investigators have suggested, another radical pair might be involved.

Many questions about the birds' magnetic compass remain, including whether the magnetic field effects on robin Cry4a observed in vitro also exist in vivo. We also want to see whether migratory birds with genetically suppressed Cry4a production are prevented from orienting using their magnetic compass. If we can prove that a radical-pair mechanism is behind the magnetic sense in vivo, then we will have shown that a biological sensory system can respond to stimuli several million times weaker than previously thought possible. This insight would enhance our understanding of biological sensing and provide new ideas for artificial sensors.

Working to gain a full understanding of the inner navigation systems of migratory birds is not merely an intellectual pursuit. One consequence of the enormous distances migratory birds travel is that they face more acute threats to their survival than most species that breed and overwinter in the same place. It is more difficult to protect them from the harmful effects of human activity, habitat destruction and climate change. Relocating migratory individuals away from damaged habitats is rarely successful because the birds tend to instinctively return to those unlivable locales. We hope that by providing new and more mechanistic insights into the ways in which these extraordinary navigators find their way, conservationists will have a better chance of "tricking" migrants into believing that a safer location really is their new home.

When you next see a small songbird, pause for a moment to consider that it might recently have flown thousands of kilometers, navigating with great skill using a brain weighing no more than a gram. The fact that quantum spin dynamics may have played a crucial part in its journey only compounds the awe and wonder with which we should regard these extraordinary creatures. SA

FROM OUR ARCHIVES

The Big Day. Kate Wong; October 2021.

scientificamerican.com/magazine/sa

ASTROPHYSICIST Ekta Patel, a postdoctoral fellow at the University of California, Berkeley, studies satellite galaxies around the Milky Way and Andromeda.

ASTRONOMY

WOMEN TAKE ON THE STARS

A new wave of astronomers are leading a revolution in scientific culture

By Ann Finkbeiner

Photograph by Timothy Archibald

Ann Finkbeiner is a science writer based in Baltimore. She specializes in writing about astronomy and cosmology, grief, and the intersection of science and national security. She is co-proprietor of the science blog The Last Word on Nothing.

SOME YEARS AGO I MADE UP A LIST OF THINGS I WAS TIRED OF READING in profiles of women scientists: how she was the first woman to be hired, say, or to lead a group, or to win some important prize. I had just been assigned a profile of a splendid woman astronomer, and her "firsts" said nothing about the woman and everything about the culture of astronomy: a hierarchy in which the highest ranks have historically included only scientists who are male, white and protective of their prerogatives. My list evolved into the "Finkbeiner test," and to abide by it, I pretended we had suddenly leaped into a new world in which gender was irrelevant and could be ignored. I would treat the person I was interviewing like she was just an astronomer.

Later, working on another story, I started hearing about a cohort of young women astronomers who were the ones to call if I wanted to talk to the field's best. If the top of the scientific hierarchy now included large numbers of women, I wondered whether they might live in a post–Finkbeiner test world—that is, whether they were just astronomers, not "women astronomers." I turned out to be 180 degrees wrong. True, they are at the top, but they are outspokenly *women* astronomers, and they are remaking astronomy.

Earlier generations of women had worked against the restrictions of the hierarchical culture, but change was glacially gradual, partly because the women were few. With time, however, small changes in their numbers added up and then tipped over, creating a different world. This recent cohort of women, who earned doctoral degrees around 2010, wins prizes, fellowships and faculty positions; does not suffer foolishness; and goes outside the established rules to make its own. "We create the culture we want," says Heather Knutson, who won the Annie Jump Cannon Award in 2013. She is a full professor at the California Institute of Technology and studies the properties of exoplanets. "There are more of us now, and we have the power to shape it."

One of the rules of their world is that it includes not only women but also people who have been marginalized for other reasons, that is, people of color, disabled people, LGBTQ+ people and those who are nonbinary—people whose numbers in the field are still strikingly unrepresentative.

These women astronomers are scientifically and culturally ambitious, and they shine of their own light; they sparkle. Their world still has restrictions but not as many, and the women react to them more defiantly. "We don't want to change ourselves to fit the mold," says Ekta Patel, a Miller postdoctoral fellow at the University of California, Berkeley, who simulates the behavior of satellite galaxies. "I enjoy being a girl," says Lia Medeiros, a National Science Foundation postdoctoral fellow at the Institute for Advanced Study in Princeton, N.J., where she studies black holes. "And I'm going to be a girl all over their physics. This is my world, too."

WOMEN HAVE BEEN ASTRONOMERS since forever, but they have needed to be made of iron. Vera C. Rubin, who got her Ph.D. in 1954, was advised in school to stay away from science. She kept going anyway by telling herself she was just different from other people. She did her graduate studies where her husband's job took them, raised children and then got a position where she was the only woman. She discovered the first solid evidence of the dark matter that, years later, is still one of cosmology's biggest mysteries. She was elected to the National Academy of Sciences (NAS), won the National Medal of Science and, after she died in 2016, had an ambitious observatory named after her; one of its missions is to map dark matter.

Back in 1965, Rubin confronted the Hale Telescope's no-women-allowed rule, ostensibly imposed because observing is an all-night process and the observatory had no ladies' room. Rubin

SARAH HÖRST, a planetary scientist at Johns Hopkins University, studies atmospheric chemistry.

cut a piece of paper into the shape of a woman with a skirt and pasted it on a bathroom door, creating the Hale's first ladies' room.

Rubin was extraordinary, but her work conditions were dead standard. All women astronomers in her world—those earning doctorates between the mid-1950s and the mid-1980s—had the same stories, which disconcertingly often mention bathrooms. The women were not admitted, were not allowed, built careers around their families, developed thick shells impervious to aggression and were almost completely isolated. Their best bet was to blend in with the male culture of astronomy. Margaret Burbidge—Ph.D. 1943, co-discoverer of the formation of the universe's chemical elements, awarded the National Medal of Science and elected to the NAS—refused the women-only Annie Jump Cannon Award because she thought women should be discriminated neither against nor for. A woman astronomer in Rubin's world was so alone as to be virtually *sui generis*—one of the few of her kind. Meg Urry, Israel Munson professor of physics and astronomy at Yale University, says that for her, Rubin was an "existence-proof."

But in the 1960s and 1970s a series of court decisions, affirmative-action policies, laws and executive orders mandated that universities no longer exclude women and minorities for either study or employment. By the time Urry got her Ph.D. in 1984, some constraints on Rubin's world were illegal, and others were publicly deplored.

By 1987 Urry was working at the Space Telescope Science Institute (STScI) on active galactic nuclei, unusually bright objects accompanied by light-years-long jets. She found that a subset of these objects were the same creature, eventually shown to be a supermassive black hole embedded in a galaxy and sending out jets. STScI was then only six years old, and of the first 60 scientists it hired, 59 were men. In 1992 Urry organized a series of conferences, eventually run by the American Astronomical Society (AAS), on women in astronomy. That year's meeting was held in Baltimore. The resulting advisory, called the Baltimore Charter, pointed out that as long as women were in charge of familial life, their careers were going to look different from men's. It recommended, among other things, "swift and substantial action" against sexual harassers and imple-

Photograph by Amanda Andrade-Rhodes

mentation of the tenets of affirmative action—including, most radically, Urry says, that hiring shortlists should include at least one woman. But the biggest impact of that first conference, Urry says, "was being in a room with 200 women astronomers. Before that you'd meet three women in the ladies' room, so this was a huge and shocking thing."

UNIVERSITY OF WASHINGTON'S astronomy department includes (*from left*) Jessica Werk, Emily Levesque and Sarah Tuttle.

Demographic surveys of Urry's world—women who got their Ph.D.s roughly between 1985 and 2010—show that in the 1990s women were just under 15 percent of the astronomy postdocs and assistant and associate professors and around 5 percent of the full professors. Given their low numbers, women in this environment still thought it best to blend in with the established culture. "In Meg's world," says Nicolle Zellner, Ph.D. 2001, co-chair of the AAS's Committee on the Status of Women in Astronomy and a full professor at Albion College in Michigan, "women worked hard, fit in and hoped to be rewarded."

Over time the number of women slowly went up to almost enough. In 1999 women were about 16 percent of the assistant and associate professors of astronomy; in 2013 they were around 22 percent. In 1999 women were 7 percent of the full professors; in 2013 they were 14 percent. These changes in numbers, Urry says, drove changes in policy and practice.

Institutions and professional societies increasingly adopted the Baltimore Charter's ideas, including offering affordable child care and parental leave, adapting tenure deadlines to family circumstances and publishing codes of conduct. Prizes began to allow self-nomination, avoiding some of the bias of the nomination process.

Eventually women's increased numbers and reduced restrictions created widespread conditions for what I think of as sparkle. Sparkle is a fireworkslike quality, noticeable in talks and conversations, that in earlier generations of astronomers was most obvious in young men: visible brilliance, intensity, easy confidence and a springy joy. Quantifying sparkle is tricky. Most of its metrics—time on telescopes, named invited talks, citations for papers, leadership of teams—are hard to define and count precisely. But some examples illustrate the point. See, for instance, the fraction of prizes given to women by either the Kavli Foundation or the AAS for general scientific contributions: from 2001 to 2005 it was 4 percent; 2006 to 2010, 12 percent; 2011 to 2015, 23 percent; 2016 to 2021, 30 percent. Or the fraction of panel seats granted to women for the NAS's decadal surveys to decide the future course of astronomy: 1990, 8 percent; 2000, 15 percent; 2010, 27 percent; 2020, 43 percent. Or look at prestigious postdoctoral fellowships that award research money to be taken to whatever institution one chooses, including the Chandra, Sagan, Einstein and Hubble postdoctoral fellowships. From 1996 to 2010, between 24 and 28 percent went to women; 2011 to 2015, 31 percent; 2016 to 2021, 45 percent. In 2021, of the now merged Sagan Einstein Hubble fellowships, awarded by NASA, women won 58 percent.

Notably, somewhere around 2015 the lines charting all three metrics took a fast turn to the northeast. Moreover, women in this post-2015 subcohort are visibly "badasses," says Jessica Werk, Ph.D. 2010, a Hubble fellow and associate professor at the Uni-

Photograph by Annie Marie Musselman

versity of Washington who studies the gas in and around galaxies: "They *really* don't take people's shit."

CAITLIN CASEY, PH.D. 2010, was a Hubble fellow, won the AAS's Newton Lacy Pierce Prize and is now an associate professor at the University of Texas at Austin. She studies the lives of early massive galaxies, best observed at many wavelengths and in enormous surveys with teams of hundreds. She leads two teams, one surveying millions of galaxies using the major telescopes in space and on the ground and the other for an upcoming survey, using the James Webb Space Telescope, to look back to a billion years after the beginning of time for young galaxies.

When she was a postdoctoral researcher, Casey heard advice from senior scientists about navigating academia: "Work extra hard. Take telecons at 4 A.M. Put your head down until you're safe." She and her friends, also in junior positions, thought the advice was bad. They told one another, "That's a load of crap. Why don't we do our own thing and see if we get hired?" She was hired. As a new faculty member, she was again advised against activism before tenure. "I worried about that, but I decided to ignore it," she says. "I got tenure." Every time she gets similarly bad advice, she says, "I muster the presence of these other women."

The sparkly cohort knows that its backbone is based on the presence of other women. Sarah Tuttle, Ph.D. 2010, an assistant professor at the University of Washington, builds instruments to study nearby galaxies. "When there are three of us," she says, "we can spread out the work; there's more room to throw elbows." Laura Chomiuk, Ph.D. 2010, a Jansky fellow and associate professor at Michigan State University who studies novae, adds, "I do feel like I have allies. I can always find an ally." They either join networks or start their own. They have lunches, meet at conferences, buttonhole departmental women visitors, set up private Facebook pages and Slack channels, and are all over Twitter. "Every university I've been at has had a women's group," says Danielle Berg, Ph.D. 2013, an assistant professor at the University of Texas at Austin who studies the evolution of star-forming galaxies.

If you feel a group has your back, you are freer to be your own individual self. "I don't want to be a blank-faced robot astronomer," says Sinclaire Manning, Ph.D. 2021, a Hubble fellow at the University of Massachusetts Amherst who studies brilliant dusty young galaxies. "I can't not be a Black woman, and I would never hide that I am." Berg had purple hair and wore a bright green suit to a job interview, and, she says, "they decided that was a good thing." With backing, you are also free, like Casey's friends, to disagree with established culture. Sarah Hörst, Ph.D. 2011, an associate professor at Johns Hopkins University, studies atmospheres around planets and moons. She told me, "My first year here I thought, if I have to sit through this for seven more years [until tenure], what I will be at the end of it is not going to be someone who changes things. If I had to sit quietly during faculty meetings, I'd have quit."

Some of what they are not sitting quietly through is astronomy's traditionally sexist, aggressive culture—people on committees saying things like, "Sure, she's pretty enough to hire," remembers Laura Lopez, Ph.D. 2011, who was both a Hubble and an Einstein fellow and is now an associate professor at Ohio State University studying the lives and deaths of stars. "In the Zoom era, I can immediately message the department chair and say, 'Speak up right now,' and he does."

When people in the audience at a presentation ask questions belligerently, Berg responds, "Do you feel better? Can I continue?" Catherine Zucker—Ph.D. 2020, a Hubble fellow at STScI who works on the interstellar medium—redirects: "I just say, 'Let's touch base afterward,' and no one ever does."

MOST NOTABLY, the new generation of astronomers is not being quiet about sexual harassment, which, in spite of great publicity and its breach of every code of conduct at every institution, is still common: a 2018 NAS report found that 58 percent of women in STEM academia had been sexually harassed, and only 6 percent of them reported it. But a discontinuity may have occurred in 2015 when an ongoing sexual harassment case involving prominent astronomer Geoffrey Marcy was reported by BuzzFeed and then many other major publications. Women now file harassment cases more often and name names, not only in the old whisper networks but also in the news and social media.

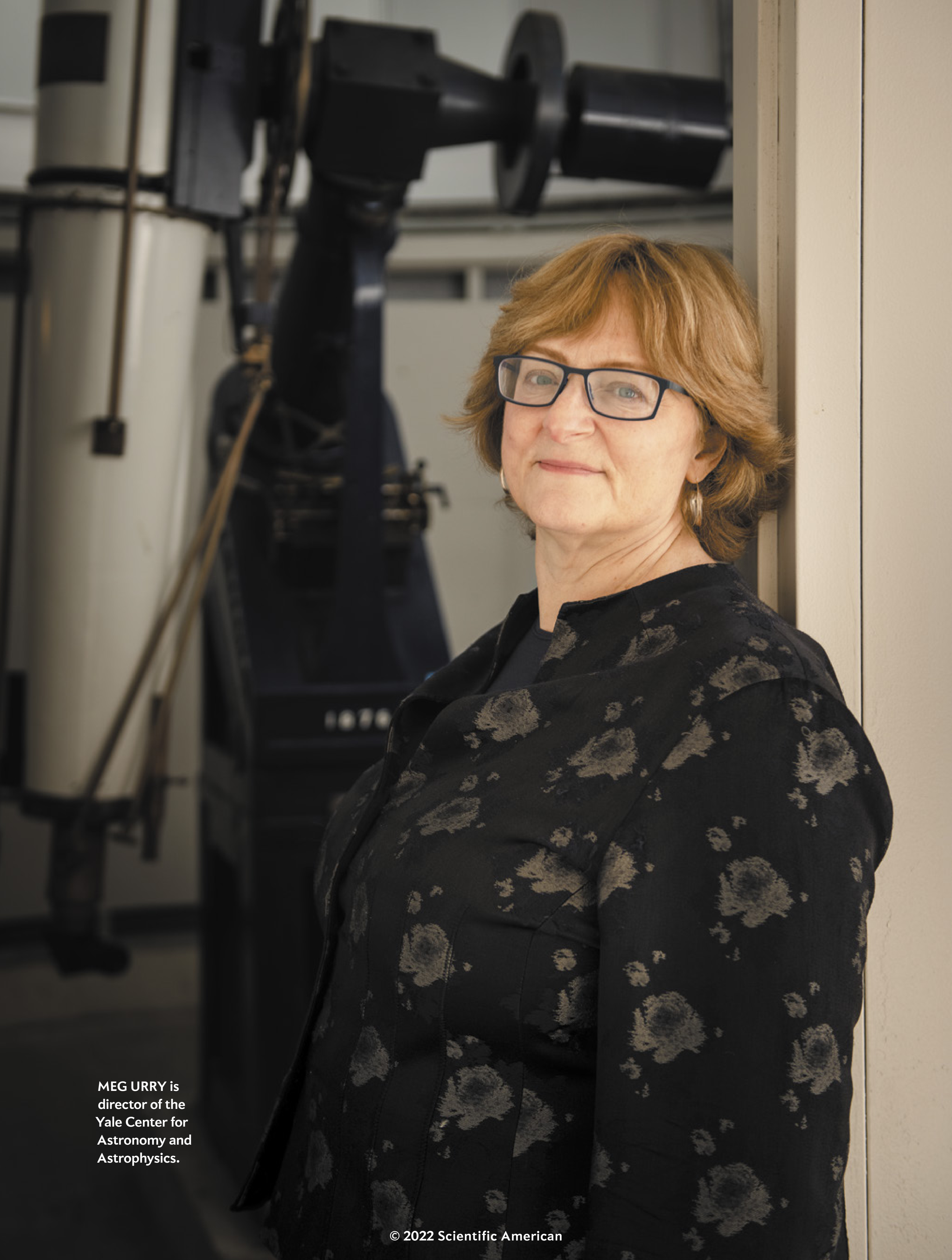
Emily Martin, Ph.D. 2018, a 51 Pegasi b fellow at the University of California, Santa Cruz, who builds instruments to study exoplanets, was a graduate student when her lab's married deputy director repeatedly said he had feelings for her. When she did not reciprocate, he confronted her. Nearing the end of her doctorate and feeling safer from him, she filed for a formal investigation with the Title IX office in charge of enforcing the university's sexual harassment policies. The office concluded that his behavior did not break policy by hindering her, because she had finished her degree and obtained a postdoctoral position. So she wrote an account for the Web site Medium, naming him.

Hörst reported a man who sexually harassed her to her university, but officials claimed he had done nothing wrong. She had been told that the same man had harassed other women, and because the others, worried about his vindictiveness, did not want to make his name public, Hörst agreed not to name him. She has suggested to conference organizers that the orientation of poster rows in meeting rooms should be changed so that presenters standing by theirs are always publicly visible and cannot be cornered.

Kathryne Daniel, Ph.D. 2015, an assistant professor at Bryn Mawr College who works on theoretical galactic dynamics, says when she is sexually harassed, "I let them pretend it didn't happen, [or] I say, 'You must be so embarrassed.' There are no robust ways of reporting that protect the reporter."

Chomiuk has not been harassed, but when a proposed faculty visitor turned out to be an astronomer who was then on leave without pay from Caltech for sexual harassment, she argued against the appointment. This "led to drama," she says. Others apologized for him; people told Chomiuk "he says he didn't do it" and "we'd bring him in for the science." But in the end the department agreed with her. "I could have just let it go," she says, "but aaargh, I couldn't."

Uncertainty about whether your career will go up in flames, cynicism about institutional responses, advocacy on behalf of others and worry about the harassers' next targets are all standard responses to sexual harassment. In spite of the difficulties, young women increasingly do not let it go. Casey wrote a chain of tweets listing her own experiences and added, "To all the young folks out there: document abuse. If you don't want to share it now, one day you'll be in a position of greater power/freedom."



MEG URRY is director of the Yale Center for Astronomy and Astrophysics.

THE OTHER ISSUE that young women astronomers speak up about is bias, the deep cultural belief that, for instance, women are good at certain things, and science is not one of them. Like sexual harassment, bias, both unconscious and explicit, is widely acknowledged and is covered in every code of conduct. Where it was once endemic and obvious, it now is slightly less endemic and operates just below the visible level. Urry has been on hiring and promotion committees for the past 30 years and says she still sometimes sees a man presented as a genius when he has not quite "done his genius thing yet," whereas people question whether a woman with comparable accomplishments did the work on her own. Melodie Kao—Ph.D. 2017, a former Hubble fellow and current Heising-Simons 51 Pegasi b fellow at the University of California, Santa Cruz, who studies the magnetic fields of planets and low-mass stars—says she herself has had to actively resist being harder on women's proposals.

A partial solution, beginning in 2018, has been to implement a system of "dual-anonymous" proposal review, that is, one in which neither the reviewers nor the proposers know the other group's identities. The major funding agencies and observatories now use dual-anonymity, and although the results are based on a small sample, the success rates of women's proposals seem to have gone up, albeit not dramatically. "We're moving from conscious, overt, unapologetic discrimination to unconscious bias," says Laura Kreidberg, Ph.D. 2016, who won the Annie Jump Cannon Award and is the founding director of the department of atmospheric physics of exoplanets at the Max Planck Institute for Astronomy in Heidelberg, Germany. "For now it's strong, but I have a huge amount of hope of getting rid of it."

Because bias and sexual harassment seem to have deep, perennial roots, a few young women say that they initially wanted to burn the whole system down. But then they thought that rather than destroy a culture, they could make their own. "We've come to know each other in enough numbers," Daniel says, "[that] we can start to make sure a woman is in every decision-making room."

Kreidberg is creating a wholly new department at her institution. She wants thinking to be more collaborative, "done at a blackboard," she says. "I want juniors to speak up and ask questions. And I want people to not have so many responsibilities they can't be creative—there's no way around long hours at the cost of other things, but I have a family, I'm a runner, I tango, and without these breaks, I run out of ideas." Berg leads a 50-person team: "Everyone knows what's going on; no cliques, and no cutting people out." Casey co-leads a group of more than 200 people whose rules are, "Don't worry about papers that disagree, address it in a future paper, and don't be a dick. Respect the human, let the science happen, and it'll work itself out."

This young cohort of women astronomers is exquisitely aware of earlier generations' generosity and of its own responsibility to future scientists. "We recognize the generations of women who reached down and pulled us up, and a lot of us think now we need to do the same," Werk says. Urry estimates that she has spent roughly a quarter to a third of her career changing the conditions for women. "You have to stay in the field to change things," Hörst says. "If it had been intolerable for Meg [Urry], I wouldn't be here."

Most of these young women mentor undergraduate and graduate students who are not necessarily their assigned advisees. Kao teaches workshops that she markets as being on early-career skills but that are also about vulnerability and emotions, "how we know when we need to tend to our boundaries or to take better care of other people." Others run programs and workshops on the entire constellation of bias issues. They offer classes for children interested in science. They serve on their institutions' Diversity, Equity and Inclusion (DEI) committees, and they note that the DEI work tends to be done mostly by women and minorities. "I'm trying to think of a woman who is not an activist," Medeiros says. Their activism in the past 10 or so years has particularly focused on the demographic populations whose numbers in the field are still too low: "Things are better for us," Knutson says, "but 'us' is still white": white people make up 60.1 percent of the U.S. population and 82 percent of astronomers. Astronomy's demographics are disturbing: 18.5 percent of Americans are Hispanic or Latino, but 5 percent of astronomers are; 13.4 percent of Americans are Black, but 2 percent of astronomers are. A recent NAS report called the numbers of people of color in astronomy "abysmally low."

"I'm a first-generation woman of color who has to learn a completely new world," says Melinda Soares-Furtado, Ph.D. 2020, a Hubble fellow at the University of Wisconsin–Madison, who studies stars with odd chemical abundances. "I can code-switch, but it's exhausting." Kao is first-generation Taiwanese-American: "From day one I've struggled to belong in the space I'm in. Half the time I want to change my name." Lopez says, "I'm Mexican-American and have cerebral palsy, so that's another set of hurdles." She once went to a meeting with maybe 40 people whose sexual orientation and race or ethnicity were something other than straight and white, and she was shocked at "how many of us had encountered the [assumption that] our advisers had done our work."

The restrictions that people at these intersections deal with resemble the barriers of Rubin's world: being the only one like you in the room means sometimes wondering whether you should even be in that room, and it means the other people in the room sometimes think you are incapable of doing what you have just done. "I'm never the only woman there, but for sure I'm the only Black woman," Manning says. "Isolation is weird—some days it's 'Why don't I go where I'm not being looked at like this,' and some days it's 'No, I need to be here so someone else can see me.'"

When I started talking to this bunch of young and sparkly women, I thought they might describe themselves as just astronomers, not women astronomers. What they have done is more interesting: they have reframed "astronomy" to necessarily include "women"—they have merged "women" into "astronomy."

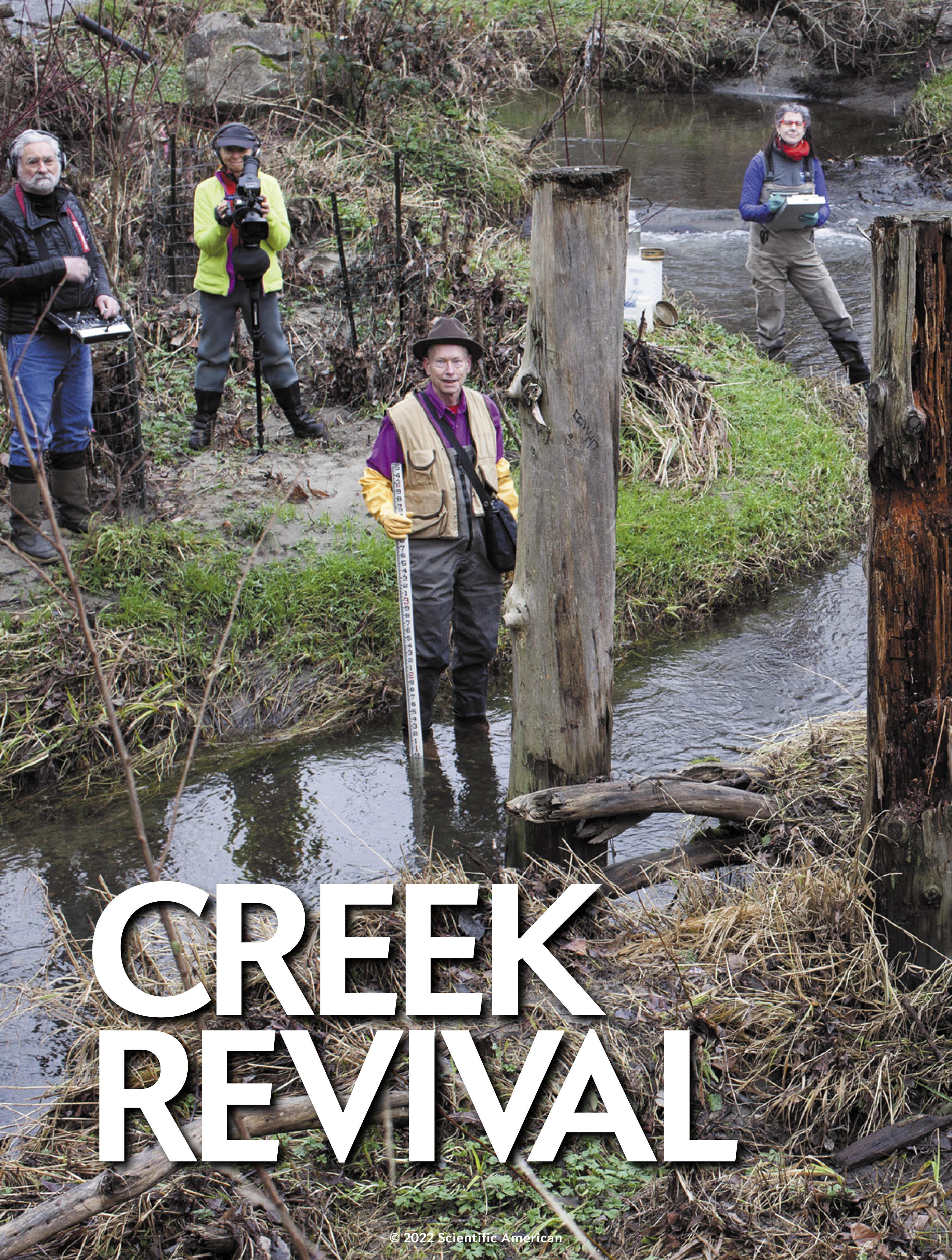
For instance, those of them offered the Annie Jump Cannon Award that Burbidge rejected have accepted it with pleasure and not as a prize for people who would not otherwise win prizes. The point, they say, is that they are women; they cannot escape it, and they might as well go ahead and have green hair, wear dresses to conferences and win women's prizes. They have been intelligent, creative and hardworking all along, but now they are also conspicuous; they have made themselves, as Manning says, seen. They are like Vera Rubin, slapping the lady-shaped icon on the door and telling the rest of their world to get used to it. SA

FROM OUR ARCHIVES

How to Fix Science. October 2018.

scientificamerican.com/magazine/sa

Photograph by Kholood Eid



CREEK REVIVAL

Radical reconstruction in Seattle is bringing nearly dead urban streams back to productive life

By Erica Gies

Photographs by Jelle Wagenaar

STREAM TEAM led by biologist Katherine Lynch (*foreground*) revived Thornton Creek by rebuilding its gut—a thick layer of wet earth, rich in microbes, hidden underneath the streambed.

Erica Gies is author of *Water Always Wins: Thriving in an Age of Drought and Deluge* (University of Chicago Press, 2022). She wrote our December 2018 article "Sponge Cities" about restoring natural water resources in urban areas.

SALMON ARE SO ELEMENTAL TO INDIGENOUS PEOPLES WHO LIVE ALONG NORTH AMERICA'S northwestern coast that for generations several nations have called themselves the "Salmon People." But when settlers came, their forms of agricultural and urban development devastated the mighty fish. The new inhabitants cut down streamside vegetation that once slowed and absorbed rains, causing floods. They straightened curvy creeks to try to speed floodwater off the land and armored the sides to prevent erosion, but the faster flow gouged the riverbed. Later, urban planners and engineers funneled streams into buried pipes so they could build more city on top, disconnecting waterways from soil, plants and animals. The cumulative impact of these injuries led to flash floods, unstable banks, heavy pollution and waning life. The hallowed salmon all but disappeared.

Across North America and the world, cities have bulldozed their waterways into submission. Seattle was as guilty as any until 1999, when the U.S. Department of the Interior listed Chinook salmon as threatened under the Endangered Species Act. That legally obligated the city to help the salmon when undertaking any new capital project that would affect the fish. Engineers trying to improve Seattle's ailing streams began to reintroduce some curves, and insert boulders and tree trunks, to create more natural habitat, yet by and large, salmon did not return. Flooding also remained a hazard because rain rushed off the hardened cityscape into the still mostly inflexible channels, which overflowed.

In 2004 biologist Katherine Lynch was sitting through yet another meeting on how to solve these problems—this one held by her employer, Seattle Public Utilities—when she had an epiphany. Maybe restoration projects were failing because they were overlooking a little-known feature damaged by urbanization: the stream's "gut."

A stream is a system. It includes not just the water coursing between the banks but the earth, life and water around and under it. Lynch had been tracking discoveries about a layer of wet sediment, small stones and tiny creatures just below the streambed called the hyporheic zone—a term from the Greek *hypo*, meaning "under," and *rheos,* meaning "flow." Stream water filters down into this dynamic layer, mixing with the groundwater pushing up. Water in the hyporheic zone flows downstream like the surface water above it but orders of magnitude more slowly.

For a large river the hyporheic zone can be dozens of feet deep and can extend up to a mile laterally beyond the banks. It keeps the waterway healthy by regulating critical physical, biological and chemical processes, including riverbed aeration, water oxygenation, temperature moderation, pollution cleanup and food creation. Some biologists compare the hyporheic zone to the human gut, complete with a microbiome. Others call it the liver of the river.

A healthy hyporheic zone is full of life. Crustaceans, worms and aquatic insects constantly move between the zone and surface flow. Nematodes, copepods, rotifers and tardigrades also dig up and down, creating spaces for water to mix underground. Microbes proliferate throughout the zone. Water welling up from below brings oxygen to salmon eggs laid in the riverbed. Lynch realized that few people trying to restore Seattle's streams were thinking about the hyporheic zone, or that the channelizing of streams scours it away, or that putting streams in pipes disconnects the zone from the stream water above.

The meeting concerned Seattle's Thornton Creek, which originally wove through rich lowland rain forest, draining an 11.6-square-mile watershed before emptying into Lake Washington. Developers had straightened it and armored it with rocks or concrete, squeezing it into channels only a few feet wide in some places. Its 15-mile course ran along a highway for a while and carved through hundreds of backyards. Some houses were so close to the narrowed stream that their decks overhung the water. Thornton had a reputation as the most degraded creek in the city—and as a dangerous one: it flooded a major road nearly every year, blocking access to schools, a community center, hospitals, businesses and bus routes. At times homes and a high school flanking the creek also flooded.

Talk at the meeting centered on the best practices of the time: reconnecting the stream with some of its floodplains by reclaiming adjacent property, removing armoring and reintroducing native plants along the banks. Lynch boldly told the group the project should go further: rebuild the missing hyporheic zone. That would mean reclaiming space *under* the stream, filling it with sand and gravel and potentially bringing back the zone's tiny inhabitants.

As far as Lynch knew, no one had tried to rebuild a missing hyporheic zone in an urban stream. She hoped that restoring the stream's gut would help Thornton Creek better maintain itself, reducing the need for ongoing, expensive human assistance. She also argued that if the revolutionary approach succeeded, it would set a new standard for urban stream restoration at a time when flooding around the world was routinely costing human lives and billions of dollars in damages. Cities everywhere had confined and subsumed many thousands of streams, erasing them from public memory. One study found that Philadelphia had buried 73 percent

LYNCH'S VISION has brought salmon back to Seattle's most degraded creek and reduced urban flooding.

of its streams. Another study counted 66 percent buried in Baltimore. Globally many streams that remained on the surface were sick or dying. Restoring Thornton Creek's hyporheic zone could create a blueprint for enhancing biodiversity while also reducing urban flooding and drought.

Fellow scientists at the meeting were enthusiastic about Lynch's radical proposal. But at subsequent meetings she quickly encountered a basic hurdle among the other decision-makers. "People," she says, "had no idea what I was talking about."

LIFE IN THE ZONE

THE HYPORHEIC ZONE is a vibrant place. Its water chemistry, temperature and life-forms differ from those in the stream above and the groundwater below. These kinds of in-between ecosystems are called ecotones—liminal spaces that can harbor great biodiversity because species from neighboring environments mingle there, along with microbes and other critters that reside only in that space.

The tiny beings in the hyporheic zone function as ecosystem engineers, metabolizing inorganic compounds into food for plants and bugs. They move organic matter and nutrients between the zone and riverbed sediments and play a pivotal role in nitrogen, phosphorus and carbon cycles. The hyporheic also helps to regulate a stream's temperature, bringing in comparatively cooler underground water in the hot summer and warmer underground water in the cold winter.

Scientists have shown how wide and deep a hyporheic zone can reach by mapping aquatic insects and fish embryos found in soil beyond a waterway's banks. For an urban creek such as Thornton, that lateral reach might extend 30 feet from the stream channel. The depth might be three feet below the streambed.

Straightening a stream and building over its floodplain can destroy the hyporheic zone. It also compounds problems: Rain that falls on pavement and rooftops cannot soak into soil and instead races off these hard surfaces, picking up fine dirt and pollutants as it rushes into the stream. These flows, which ecologists call "flashy," create a firehose effect that scours the riverbed and the hyporheic material underneath it, laid down over centuries. Eventually what remains is the impermeable underbelly, such as shale or granite. And a straight, armored river channel often cannot contain the flashy runoff; water overflows the banks, flooding the area.

Thriving floodplains absorb potential floodwater. They also slow water, dissipating its energy and reducing erosion. Slow water more readily sinks underground, where some of it will return to the stream over time via the hyporheic, supplying water in dry times. Natural streams with a stable hyporheic have a more balanced flow between winter and summer, helping to maintain water in streams year-round, even in drought-prone areas.

All these processes enable a stream to maintain itself. If the hyporheic zone is stripped away, a stream's biological gut disappears, and the waterway has little hope of staying healthy—akin to when humans develop serious digestive tract issues because their gut microbiome has been distressed.

HYPORHEIC REBUILD

LYNCH FIRST LEARNED about the hyporheic zone in 2000 at the University of Washington, but she did not appreciate how extensive the zone is until a 2004 field trip into a forest with geomorphologist and visiting lecturer Tim Abbe. She was amazed when they stopped walking and he pointed out that the ground they were on overlaid a hyporheic zone for a nearby stream. "I'm looking around at trees and ferns," she recalls, "thinking, How is that possible?"

Born and raised in Nova Scotia, Lynch had moved to the U.S. Pacific Northwest and ended up working for Seattle Public Utilities, focusing on stream restoration. The two stretches of Thornton Creek slated for revitalization and discussed at the 2004 meeting were called Confluence and Kingfisher. They totaled 1,600 feet in length. The team chose these spans because they were originally floodplains, and allowing overflow there could greatly reduce problematic flooding along the stream's longer route. The Seattle Parks Department had already been buying out willing homeowners whose houses flooded along those stretches—five at Confluence and six at Kingfisher—so some of the creek's stolen elbow room could be restored.

Lynch knew that getting decision-makers to try something new would be hard. Urban stream restorations have big price tags and high stakes—namely, ensuring that people's properties do not flood. By 2007, after much discussion, the design plans included hyporheic restoration—although it was not approved as a formal part of the project for another seven years. That time line is typical of city projects, Lynch says, which require funding; coordination among landowners, community groups and multiple agencies; and assessments of social justice and equality.

Lynch's supervisor asked that the work include stream monitoring so scientists could provide data to inform subsequent projects. Paul Bakke, then a geomorphologist at the U.S. Fish and Wildlife Service, did baseline measurements, which confirmed that Thornton Creek's hyporheic zone had been almost completely scraped away. The utility hired Seattle-based Natural Systems Design, a science and engineering firm that restores waterways. Lynch teamed Bakke with the firm's lead engineer, Mike Hrachovec, to create the innovative design.

The restoration was personal for Bakke, who had grown up in the 1960s and 1970s along Thornton Creek, fishing for cutthroat trout and playing with water skeeters. Just before he entered high school, the city issued permits for condos along the creek's edge, cutting off his access to the water. "These old haunts that I really loved, that were my sort of wilderness … were suddenly not just blocked but being paved over," he says. "It was very upsetting."

Hrachovec also frequented streams in his youth, in South Dakota's Black Hills. Nevertheless, when Lynch paired them up to redesign Thornton Creek, the two men found collaboration rough going. In one battle, Bakke wanted to put larger gravel on the streambed so water could move more easily into the hyporheic. Otherwise, he feared, urban dust washing into the creek could plug up the downward flow. Hrachovec worried that large gravel might convey too much water underground, drying out the surface stream in summer and killing fish. This kind of uncertainty is one reason it can be hard to get a city to try something new.

Stream shape, gradient, water speed and debris also influence flow into and out of the hyporheic zone. To sort things out, the team ran tests using computer simulations and in a large sandbox, modeling stream dynamics and trying different rock aggregates, curves and wood placement to drive water underground. Satisfied at last, and with other city requirements in place, Seattle put out a call for bids in early 2014. Then, in May 2014, just before construction was due to begin, the Seattle Public Utilities project manager raised budget concerns because another project was running over. "In front of my eyes," Lynch recounts with incredulity, "he says, 'What's this hyporheic thing?' And he just cut it."

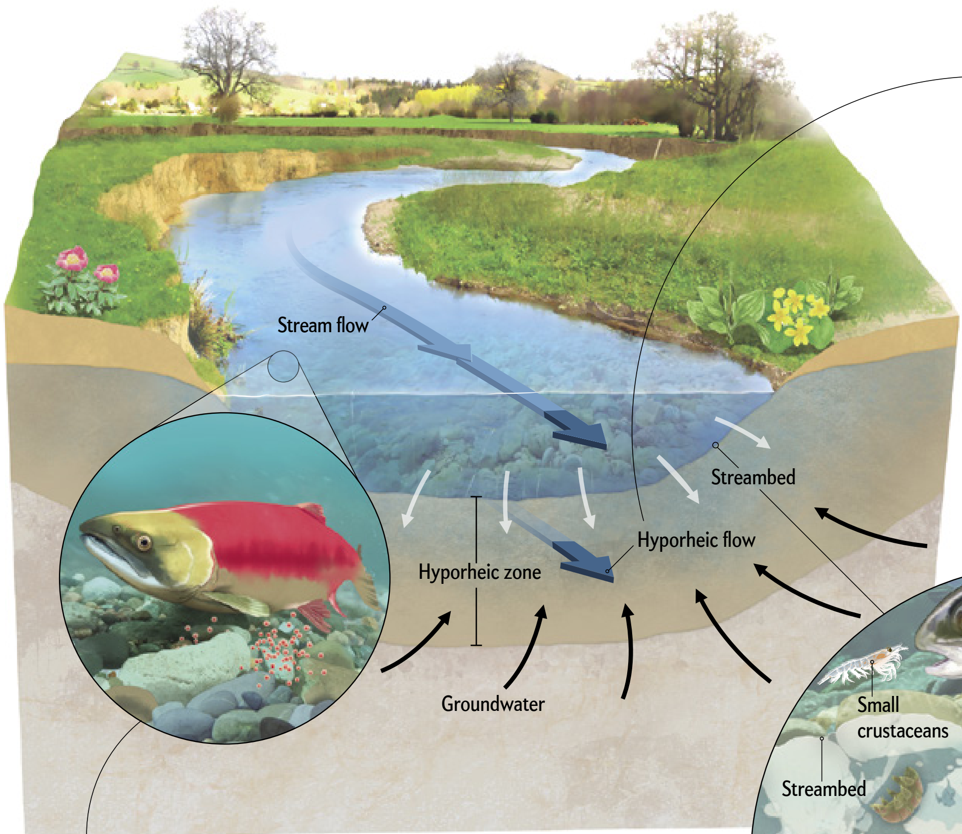
Lynch told the manager how crucial the zone was and argued that the hyporheic elements accounted for only $300,000 of the two sites' combined $10.5-million budget. She told him the investment—for excavation and materials such as boulders, gravel and finer sediment—was likely to pay off quickly. Her team had determined that rebuilding the zone would reduce the need to spend $1 million a year on average dredging sediment from a nearby stormwater pond built to absorb heavy runoff.

She also reminded the manager that the monitoring would provide lessons on how to reconstruct urban streams to something closer to their full complexity, making Seattle a leader in this work worldwide. In the end, they negotiated. Lynch was able to keep the Confluence hyporheic restoration intact; the Kingfisher reach was shortened by 25 percent.

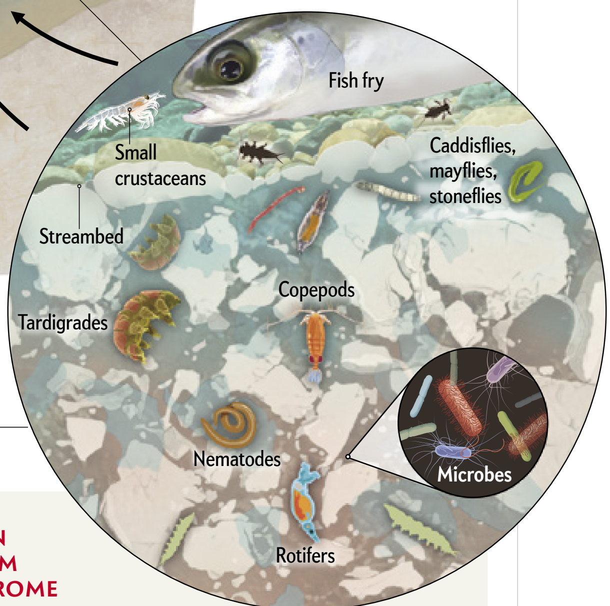
In summer 2014 the bulldozers moved in. Hrachovec and his team scooped out generous curves in the spaces reclaimed from the houses, in spots widening the creek from four or eight feet to 25 or 30 feet. To bring the creek bed to its former elevation and

Liver of the River

The hyporheic zone—little known or appreciated—is a watery layer of stones and sediment rich with tiny creatures that lies underneath a river, stream or creek bed and extends beyond the banks. It supplies a waterway with nutrients and cleanses pollutants, akin to a human's gut or liver. In cities, straightening a stream and hardening its banks often cripple the hyporheic zone, leaving the stream ill or dying.

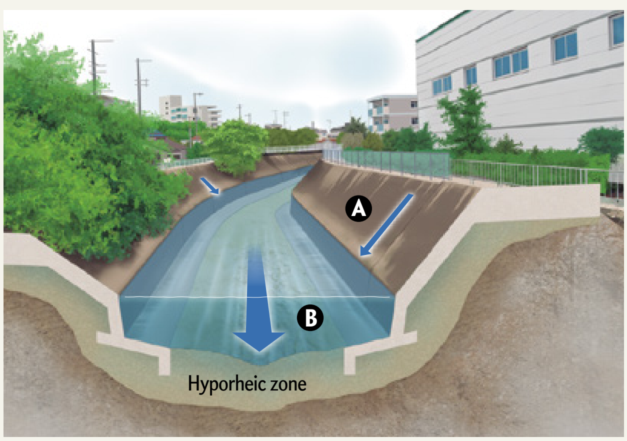


Stream water from above pushes down into the hyporheic zone, merging with groundwater pushing up from below. The mix flows downstream—though much more slowly than the surface water—and moderates extreme cold and warm stream temperatures. Rainfall, and occasional flooding outside the banks, can help recharge groundwater and the zone.



A healthy hyporheic zone provides the concentrated oxygen that fish eggs need to develop.

Many small animals live in the hyporheic zone. They dig around, helping water and oxygen flow through the creek bed, and provide food for crustaceans, fish and other creek dwellers. Microbes break down pollutants and help move nutrients such as nitrogen, phosphorus and carbon.



URBAN STREAM SYNDROME

Cities often straighten streams and harden banks, harming the hyporheic zone.

A Rainfall runs off pavement and rooftops, instead of soaking into the soil. It pours down impervious banks that have no vegetation to slow the flow and into the channel, carrying in pollutants and filling the stream so it floods.

B Heavy runoff creates a fast, downstream flow that scours out the hyporheic zone's sediment, nutrients, tiny animals and microbes, leaving it thin, bare and lifeless.

Graphic by 5W Infographics

reintroduce material that would hold the hyporheic zone, they layered in sediment and gravel nearly eight feet deep. Hrachovec and Bakke inserted logs of different sizes into the water at precise angles—some partly buried, some crisscrossing the streambed—creating tiny waterfalls, plunge pools and pockets of nearly still water that create hydraulic pressure that can force water down into the zone. These meticulously placed logs and boulders, known as "hyporheic structures," also create eddies and pockets of slow water that provide safe havens for juvenile fish and bugs—all meant to emulate features of a natural stream.

The Kingfisher reconstruction was finished by that fall and the Confluence by spring 2015. The creek's flow slowed, so sediment dropped out of the water column and began refining the stream's shape and bed. That action also reduced what had been rapid downstream sediment accumulation that the city had removed regularly at great expense. Over the next five years gravel and silt gradually built up behind the wood barriers, creating gentler grades.

The monitoring allowed Bakke and Hrachovec to track water flow by sensing temperature and following tracers. They confirmed that water was indeed moving down and through the hyporheic zone. In a 2020 paper, they reported that water was mixing there at 89 times the preconstruction rate. Data analysis proved the stream was working as Bakke and Hrachovec—and nature—intended.

But was that flow also supporting life and reducing pollution?

BUGGING THE CREEK

RESTORING A STREAM'S NATURAL SHAPE can encourage displaced plants and animals to move back in. In many cases, however, only some species return. And because the gravel and sand the team installed were sterile territory, Bakke thought they might need a biological jumpstart.

If a species is missing from an ecosystem, our instinct is simply to reintroduce it. But ecologists are painfully aware of cautionary tales such as stocking a desirable trout that inadvertently brings pathogens along with it. Even bringing back a native plant can shake up a system that has adjusted to its absence.

Kate Macneale, an environmental scientist for King County, where Seattle is located, understands this lesson. She monitors insects as a measure of stream health, rating them on what she calls the "bug score." Macneale had found a clear correlation between urbanization and lower bug scores; some species, she figured, were too sensitive to survive.

A few years ago an experience made her rethink that conclusion. Vandals had destroyed an experiment she had set up in Seattle's Longfellow Creek, which released what had been captive bugs into the "wild" of the urban stream. Two years later she was sampling fish there and found one of the bugs, a caddisfly, in a fish's gut. Caddisflies live only for a matter of weeks, so it could not have been an individual from the unintended release: it must have been a "grandkid of that individual," she says. "I couldn't believe it."

Macneale realized that some insects in reconstructed streams might be missing not because they cannot hack the conditions but because there were no nearby insects around to recolonize the water. The idea that life will return to restored creeks relies on critters migrating from healthy upstream habitats. But with Longfellow Creek, Macneale says, the headwater "is literally a Home Depot parking lot." If organisms are to recolonize restored streams, she says, "we may need to help them out."

With that insight, she got permission from King County to seed four creeks with caddisflies, mayflies, stoneflies and other species. Some of them survived. In 2019 the Thornton Creek team tried another groundbreaking move: inoculating the engineered hyporheic zone with life. In keeping with the human gut analogy, the procedure is somewhat like administering probiotics, or even a fecal transplant, to a person to restore their gut microbiome.

Enter Sarah Morley, a stream ecologist, and Linda Rhodes, a microbiologist, both with the National Oceanic and Atmospheric Administration. They harvested wild microbes and invertebrates in small baskets placed in the healthier Cedar River watershed nearby. They took a few baskets back to the laboratory to document captured species, and they buried the others in Thornton Creek's restored hyporheic zones.

Invertebrates and microbes quickly colonized the areas. But even though the number of individuals was high, the biodiversity was relatively low. According to the duo's 2021 paper in *Water,* a few of the new species proliferated, but most of the other species were similar to those in unrestored sections of the creek.

Morley and Rhodes are considering why more of their introduced species did not make it. Because this science is so new, they have not ruled out any potential explanations. The donor stream may be too different, or the restored area too small, or water quality too poor. They might have inoculated the hyporheic too soon, before small vegetation needed by some critters could grow. And yet in the guts of some trout, Lynch found aquatic insects that had not been seen in Thornton Creek for at least 20 years. "The fish are better at sampling than we are," she says. The scientists are now conducting another study with more sensitive monitoring.

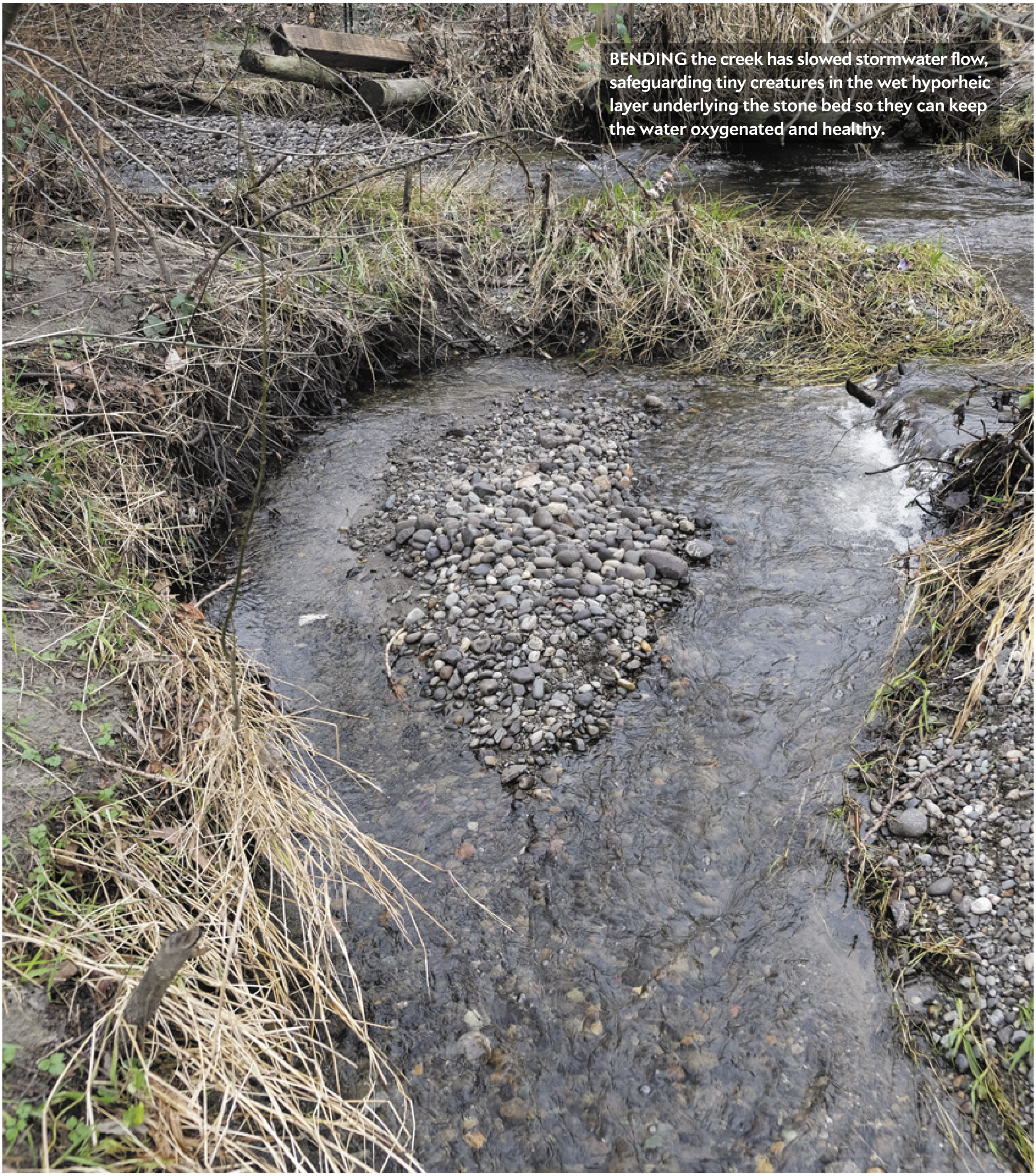
Still, Morley and Rhodes did find that the microbes that began living in the restored stream sections were much more active than those in nearby unrestored sections, indicating they were "getting goosed to do something," Rhodes says—maybe build biofilms and biomass, clean pollutants or break down organic material. The restored sections had seven times more hyporheic crustaceans, worms and insects, as well as much greater overall species diversity.

TRACKING CHEMICALS

THE FINAL QUESTION about the Thornton Creek restoration was whether it was cleaning pollution that pours in with runoff during storms, from lawn fertilizer to urban wastes. Lynch had to search for three years to find a chemist who would conduct the research. "All of them said it could not be done," she recalls. They said it was too difficult to track how long water stayed in the hyporheic zone and to measure whether chemicals were removed while the water spent time underground.

Lynch eventually reached Skuyler Herzog, then an engineer at the Colorado School of Mines, who specializes in the hyporheic zone. "He took the next plane out here," Lynch recounts with glee. After years of studying the hyporheic zone academically, he was thrilled to conduct tests on a real restoration. Lynch recruited University of Washington chemist Edward Kolodziej to help.

The team sent tracer dyes into an engineered plunge pool that pushed water into the hyporheic. They then monitored exit points seven and 15 feet downstream to determine how long a "packet" of water stayed under before rejoining surface flow; water stayed under for 30 minutes to three hours or more. They also collected water samples from the stream and used mass spectrometry to measure different pollutants from storm runoff. They counted nearly 1,900.



The scientists sampled water packets before they entered the stretches of hyporheic and after they emerged and compared them with water flowing downstream above the stretches. The surface flow reduced the concentration of about 17 percent of the chemicals by at least half. The seven-foot stretch of the hyporheic reduced the concentration of 59 percent of the chemicals by at least half, and the 15-foot stretch reduced the concentration of 78 percent of the chemicals by at least half. Because water spent so little time in those short hyporheic stretches, the team thinks the pollutants mostly got stuck on sediments or biofilms rather than being broken down immediately by microbes, although that decomposition is common over longer time periods.

Hrachovec says it is "jaw-dropping" that such short hyporheic spans were able to reduce so much pollution. He adds it was "astounding to contemplate how much good we could do if we had this more available."

BOULDERS and tree trunks inserted into Thornton Creek create protective eddies for fish and bugs. They push water down into the hyporheic zone, where it can be cleansed of pollutants before reemerging downstream. Beavers have returned close to a city neighborhood in the background.

A NEW STANDARD?

THE THORNTON CREEK findings are encouraging. The neighborhoods around the creek have not flooded since the restorations were finished in 2015, even during large storms. The stream's temperature and flow are more consistent year-round. The city needs to dredge less often, saving money, and neighbors love spending time in the expanded green space. Yet the work also reveals how complex nature's systems are and how difficult it can be to restore them once damaged. As cities and agencies increasingly turn to more nature-based solutions, the Thornton Creek lessons can help experts understand which steps work and which need improvement.

Success has helped Lynch convince Seattle Public Utilities and other city decision-makers of the importance of a stream's gut. Hyporheic restoration has become a formal part of the utilities' creek projects—not guaranteed but routinely considered. Taylor Creek now has eight planned hyporheic reconstructions along a 1,200-foot stretch. Herzog is testing design improvements to increase water's "residence time" in the hyporheic and is studying how much that increases cleansing. Plans to restore the north branch of Thornton Creek include hyporheic structures. Because of the zone's power to reduce pollution, the city will probably include hyporheic structures in a restoration along Longfellow Creek, which contains a chemical from vehicle tire particles that Kolodziej has shown kills salmon; construction could begin by 2026.

Still, small restorations cannot fully compensate for insults to long streams and rivers. "Stormwater runoff, biodiversity, flooding—these are watershed-scale problems," Bakke says. That is why reconstructions need to be distributed in many places along a stream or river. Abbe, the geomorphologist who inspired Lynch, is now at Natural Systems Design. He has planned and overseen 14 hyporheic restorations in five other Washington State counties. In 2019 Abbe was walking along a project on Poison Creek in Chelan County with Steve Kolk, an engineer with the U.S. Bureau of Reclamation, an agency infamous in ecology circles for building giant dams. As Abbe tells it, Kolk suddenly stopped walking and said, "Ultimately you're talking about hundreds of thousands of these treatments to restore our watershed." Abbe said, "Bingo."

Finding space for more natural water flows in an established city might seem difficult, but buildings are replaced more often than people think, particularly when they flood regularly. Cities can reclaim that land, as Seattle did. Even small projects in key places can make a difference. By restoring the floodplains at Confluence and Kingfisher, Seattle has relieved troublesome flooding along Thornton Creek.

Most exciting for Lynch, the hyporheic innovations won the ultimate stamp of approval in the fall of 2018, when Chinook salmon swam in from Puget Sound and spawned in the creek's restored hyporheic zones.

"That was just really emotional," Lynch recalls. "We had done it. You *can* restore the hyporheic zone. You *can* restore natural processes to the extent that we are actually attracting salmon to the site to spawn." If these two small restorations in an urban creek can help restart a functioning ecosystem, she says, "I think there really is hope for the future."

FROM OUR ARCHIVES

The Origin and Evolution of Cities. Gideon Sjoberg; September 1965.

scientificamerican.com/magazine/sa

HISTORY OF SCIENCE

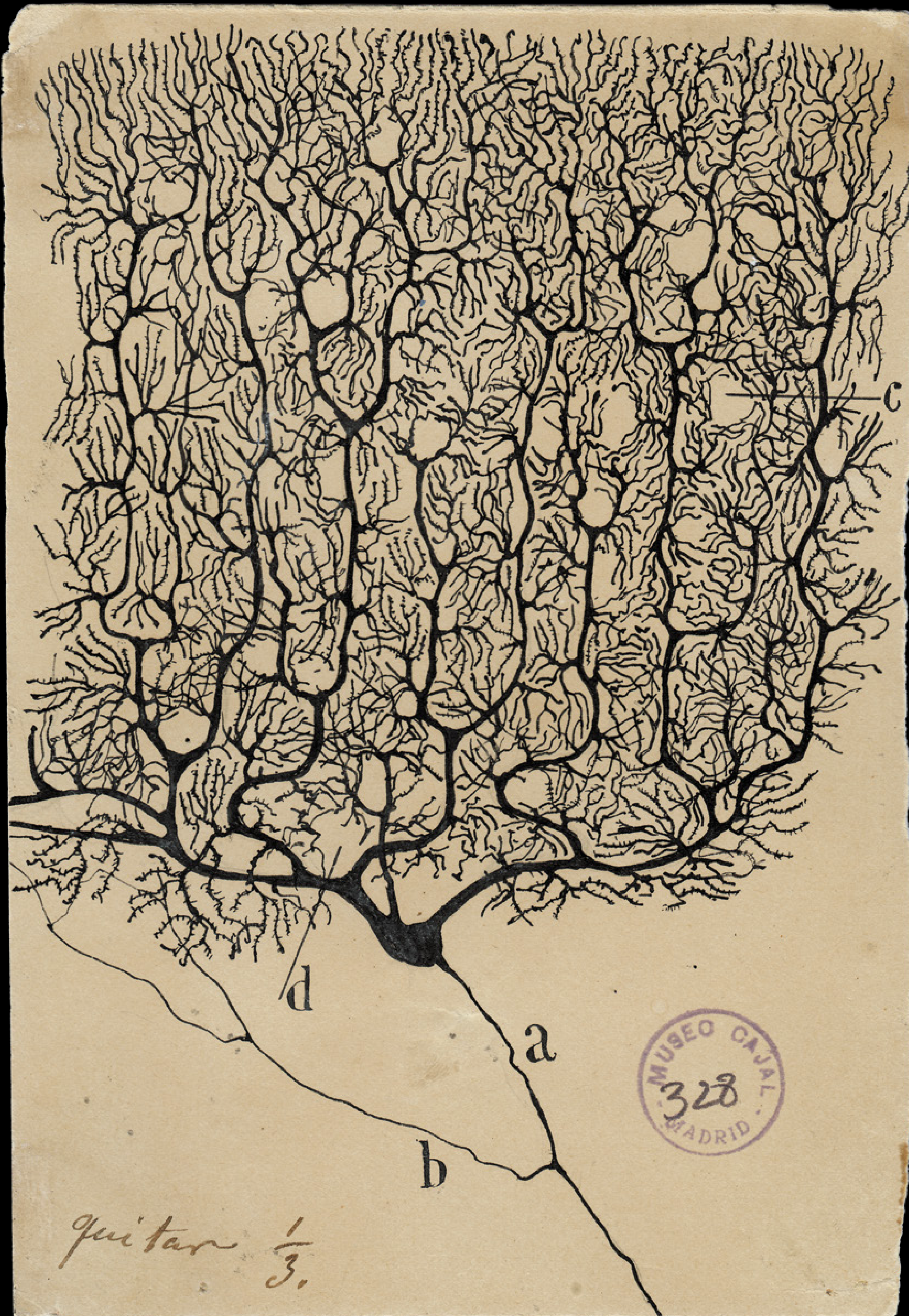
Mysterious Butterflies of the Soul

Santiago Ramón y Cajal, the discovery of neurons and the origins of modern brain science

By Benjamin Ehrlich

Excerpted from **The Brain in Search of Itself: Santiago Ramón y Cajal and the Story of the Neuron,** *by Benjamin Ehrlich. Published by Farrar, Straus and Giroux.*

PURKINJE CELL drawn by Cajal from the human cerebellum at the back of the head, which regulates balance for walking and standing.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Benjamin Ehrlich is author of *The Dreams of Santiago Ramón y Cajal,* the first English translation of Cajal's dream journals. His work has appeared in the *New England Review, Nautilus* and the *Paris Review Daily. His new book is The Brain in Search of Itself (Farrar, Straus and Giroux, 2022).*

HOUR AFTER HOUR, YEAR AFTER YEAR, SANTIAGO RAMÓN Y CAJAL SAT alone in his home laboratory, head bowed and back hunched, his black eyes staring down the barrel of a microscope, the sole object tethering him to the outside world. His wide forehead and aquiline nose gave him the look of a distinguished, almost regal, gentleman, although the crown of his head was as bald as a monk's. He had only a crowd of glass bottles for an audience, some short and stout, some tall and thin, stopped with cork and filled with white powders and colored liquids; the other chairs, piled high with journals and textbooks, left no room for anyone else to sit. Stained with dye, ink and blood, the tablecloth was strewn with drawings of forms at once otherworldly and natural. Colorful transparent slides, mounted with slivers of nervous tissue from sacrificed animals still gummy to the touch from chemical treatments, lay scattered on the worktable.

With his left thumb and forefinger, Cajal adjusted the corners of the slide as if it were a miniature picture frame under the lens of his microscope. With his right hand, he turned the brass knob on the side of the instrument, muttering to himself as he drew the image into focus: brownish-black bodies resembling inkblots and radiating threadlike appendages set against a transparent yellow background. The wondrous landscape of the brain was finally revealed to him, more real than he could have ever imagined.

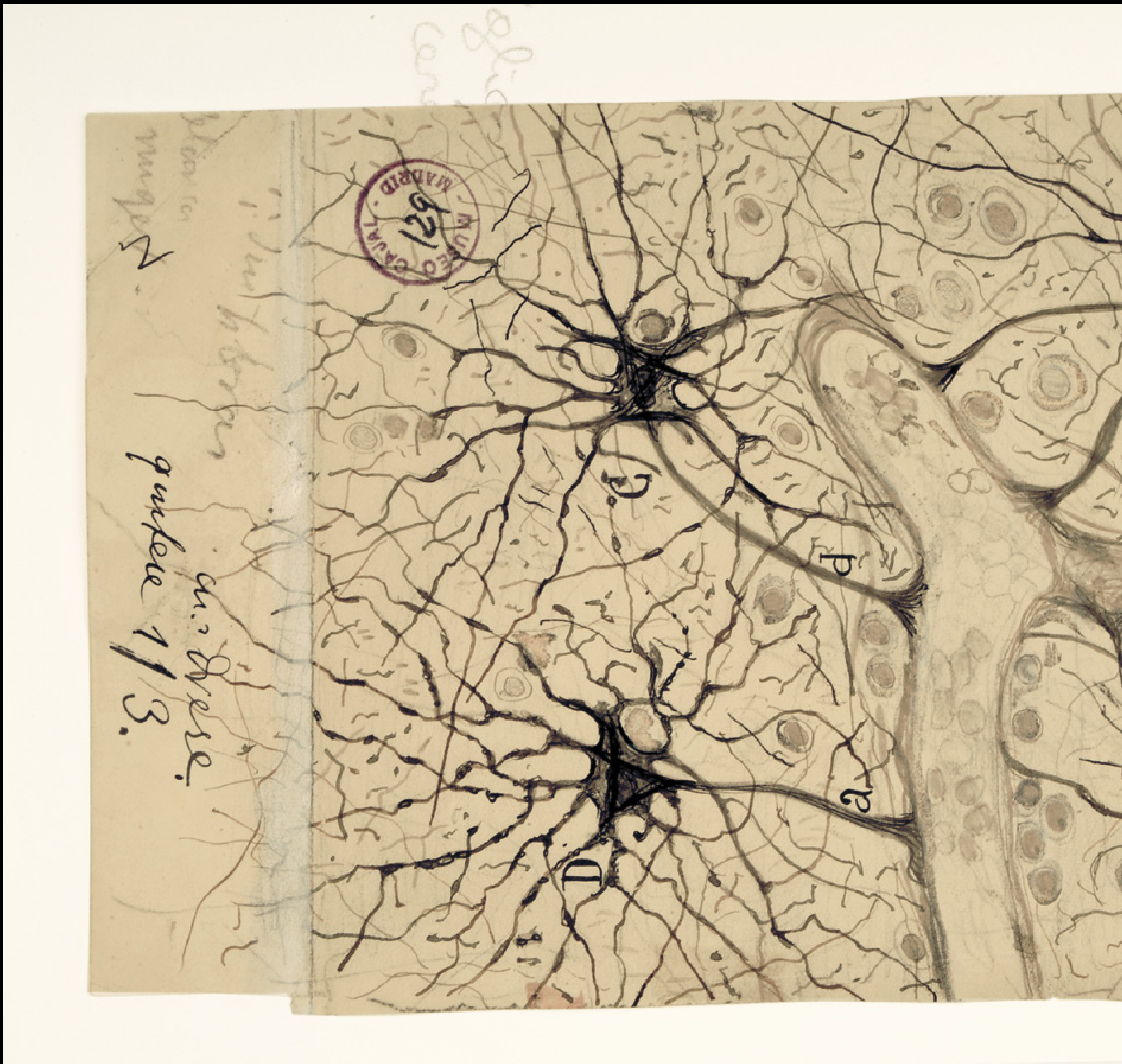
In the late 19th century most scientists believed the brain was composed of a continuous tangle of fibers as serpentine as a labyrinth. Cajal produced the first clear evidence that the brain is composed of individual cells, later termed neurons, that are fundamentally the same as those that make up the rest of the living world. He believed that neurons served as storage units for mental impressions such as thoughts and sensations, which combined to form our experience of being alive: "To know the brain is equivalent to ascertaining the material course of thought and will," he wrote. The highest ideal for a biologist, he declared, is to clarify the enigma of the self. In the structure of neurons, Cajal thought he had found the home of consciousness itself.

Cajal is considered the founder of modern neuroscience. Historians have ranked him alongside Darwin and Pasteur as one of the greatest biologists of the 19th century and among Copernicus, Galileo and Newton as one of the greatest scientists of all time. His masterpiece, *Texture of the Nervous System of Man and the Vertebrates,* is a foundational text for neuroscience, comparable to *On the Origin of Species* for evolutionary biology. Cajal was awarded the Nobel Prize in 1906 for his work on the structure of neurons, whose birth, growth, decline and death he studied with devotion and even a kind of compassion, almost as though they were human beings. "The mysterious butterflies of the soul," Cajal

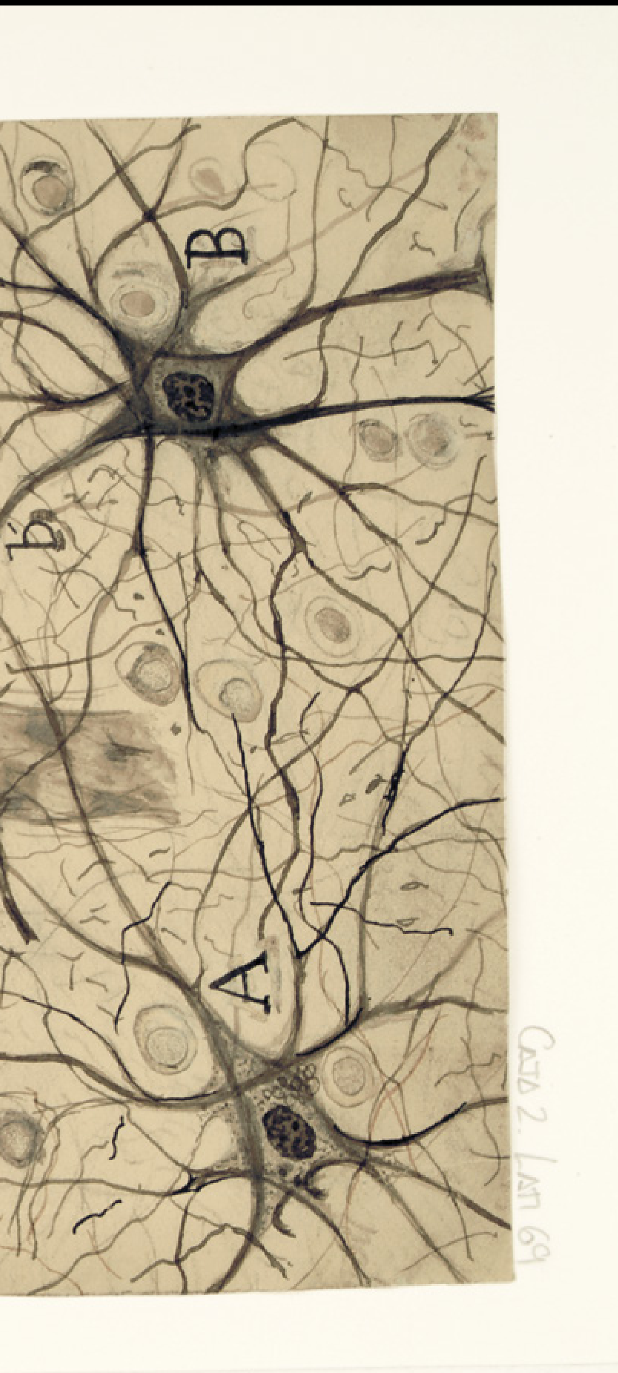
A YOUNG CAJAL appears in an 1871 photographic portrait.

Cajal Institute, Cajal Legacy, Spanish National Research Council (CSIC), Madrid, Spain (*all images*)

NERVE ENDINGS that Cajal drew from a section of mouse thalamus, a key neural signal relay point.



ASTROCYTES, support cells for neurons, surround a blood vessel.

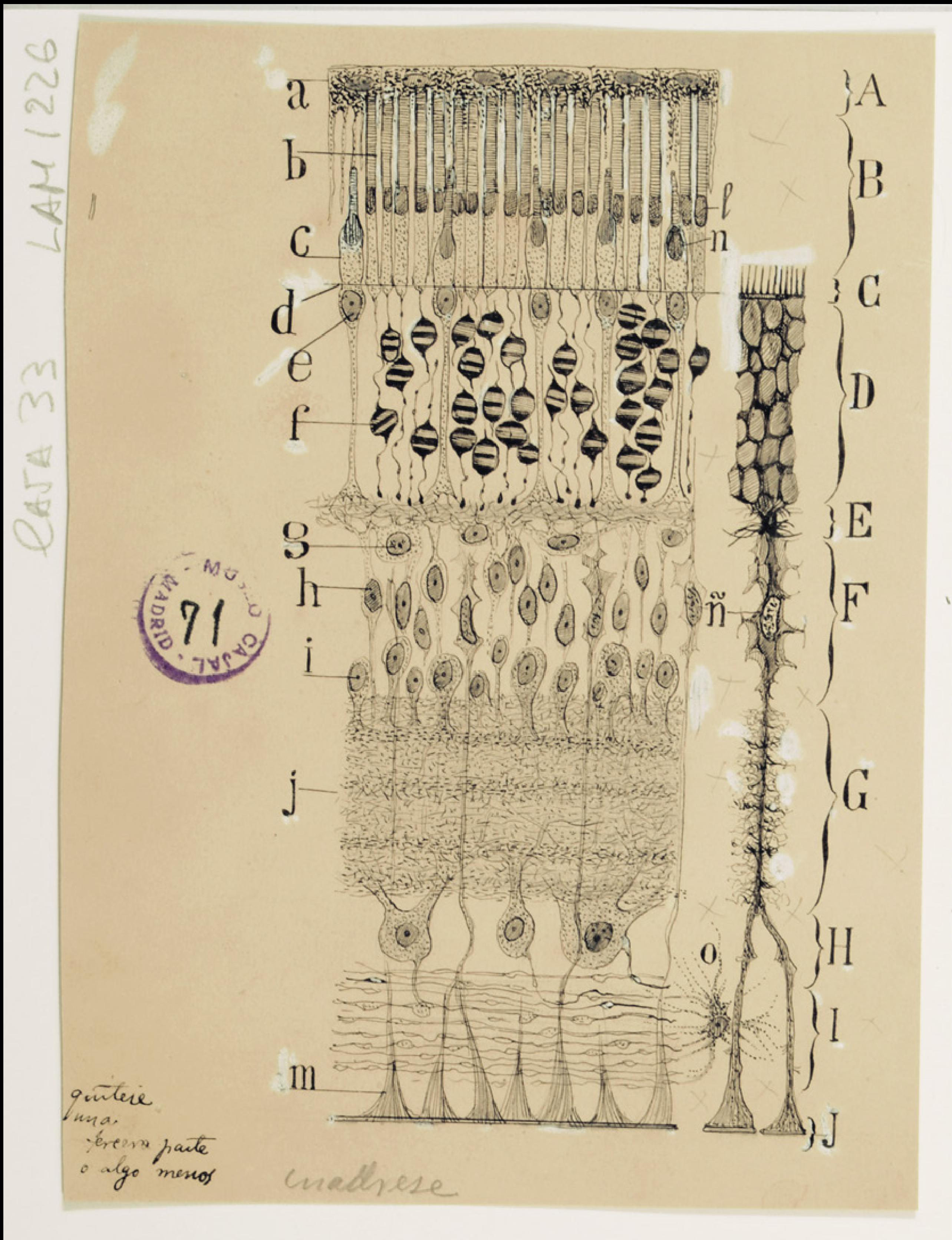


called them, “whose beating of wings may one day reveal to us the secrets of the mind.” He produced thousands of drawings of neurons, as beautiful as they are complex, which are still printed in neuroanatomy textbooks and exhibited in art museums. More than 100 years after he received his Nobel Prize, we are indebted to Cajal for our knowledge of what the nervous system looks like. Some scientists even have Cajal’s drawings of neurons tattooed on their bodies. “Only true artists are attracted to science,” he said.

A NEW TRUTH

In Cajal’s day, the most advanced method for visualizing cells was histology, an intricate and temperamental process of staining dissected tissue with chemicals whose molecules clung to the subtle architecture of the cells, rendering them miraculously visible through a light microscope. With the primitive stains available, researchers across Europe tried and failed to clarify the question of what lies inside the brain, believed to be the organ of the mind. Then, in 1873, in the kitchen of his apartment in Abbiategrasso, outside Milan, Italian researcher Camillo Golgi, through some combination of luck and skill, hit on a new technique that revolutionized neuroanatomy. “I have obtained magnificent results and hope to do even better in the future,” Golgi wrote in a letter to a friend, touting his method as so powerful that it could reveal the structure of nervous tissue “even to the blind.” He called it the black reaction. One of Golgi’s students recognized “the marvelous beauty of the black reaction ... [which] allows even the layman to appreciate the images in which the cell silhouette stands out as if it had been drawn by Leonardo.” Cajal, who first saw the technique in the home of a colleague who had recently returned from studying in Paris, was absolutely smitten. “On the perfectly translucent yellow background,” Cajal recalled, “sparse black filaments appeared that were smooth and thin or thorny and thick, as well as black triangular stellate or fusiform bodies! One would have thought that they were designs in Chinese ink on transparent Japanese paper ... Here everything was simple, clear, and unconfused ... The amazed eye could not be removed from this contemplation. The dream technique is a reality!”

Although the black reaction dramatically reduced the number of nerve elements visible on a microscope slide, those elements were still so densely packed that their fibers appeared inextricable from one another. Traditionally, researchers studied nervous tissue from adult humans who had died naturally after a normal life span. The problem was that in the adult nervous system, the fibers were already fully grown and therefore extremely structurally complex. Looking for a solution to this problem, Cajal turned to embryology—also known as ontogeny—which he had first read about in a college textbook. “If we view the natural sequence in reverse,” Cajal explained, “we should hardly be surprised to find that many structural complexities of the nervous system gradually disappear.” In the nervous systems of younger specimens, cell bodies would in theory be simpler, fibers shorter and less numerous, and the relationships among them easier to discern. The nervous system was also well suited to the embryological method because as axons grow, they develop myelin sheaths—insulating layers of fat and protein—which repel the silver microcrystals, preventing the enclosed fibers from being stained. Younger axons without thick sheaths more fully absorb the stain. In addition, mature axons, which sometimes grow to be a few feet long, are more likely to get chopped off during sectioning. “Since the full-grown forest turns out to be impen-



LAYERS OF CELLS from the retina. Cajal made studies of sections of retina from different animals, noting their structural similarities.

etrable and indefinable," he wrote, "why not revert to the study of the young wood in the nursery stage, as we might say?"

At the age of 36, Cajal found himself incubating eggs, just as he had loved doing when he was a child. This time, instead of waiting to witness "the metamorphosis of the newly born," Cajal cut into the eggshell after a few days and removed the embryo. Embryonic tissue was too delicate to withstand pressure from the clasp of a microtome. So, holding the block of tissue between the thumb and forefinger of his left hand, he cut sections with a razor blade, applying his training as a barber during the hated apprenticeships of his youth, in a fashion that he could never have foreseen. A private student of Cajal's in Barcelona who worked in the laboratory with him attested that his hand-cut sections—often between 15 and 20 microns thick—were as perfect as those cut with any machine.

In April 1888 Cajal prepared samples from the cerebellum of a three-day-old pigeon embryo. Through the microscope, he fixed his gaze on a clear, fine axon as it arced downward from its base—a soft, conical bulge on the cell body—and followed the black line, transfixed, as if he were still a boy following the course of a river. The axon curved, running alongside the layer of cells below it until it started to branch. In Cajal's eyes, the Purkinje cell stained with the black reaction resembled the "most elegant and leafy tree." He traced a branch from the cell's central "pearlike" body all the way to its end, where it approached other cells, known as stellate cells, each forming a kind of "basket" shape. Though intimately related, the "pear" of one cell and the "basket" of another never touched. Cajal sensed a "new truth" arising in his mind: nerve cells ended freely. They were distinct individuals.

THE TANGLED JUNGLE

SINCE RESEARCHERS FIRST BEGAN to study the nervous system in ancient times, they have tended to compare its structure to contemporary technologies. The ancient Egyptians saw in the exterior casing of the brain, with its fissures and convolutions, the corrugated slag left over from smelting ore. The ancient Greeks thought the brain functioned like a catapult. René Descartes believed that animal spirits flowed from the brain through hollow nerves and inflated the muscles, just as hydraulic fluid traveled through machines in the royal gardens at Saint-Germain. In the 19th century, a new era of transportation, anatomist Otto Deiters, among many others, conceived of the nervous system as a railroad, with junctions at which traffic could be routed.

In the mid-19th century the railway metaphor for the nervous system gave way to another transformative technological advance: the telegraph. The German biophysical school, headed by Hermann von Helmholtz and Emil du Bois-Reymond, led the charge. "The wonder of our time, electrical telegraphy, was long ago modeled in the animal," du Bois-Reymond said in an 1851 speech. He argued that the similarity between the nervous system and the electrical telegraph ran far deeper. "It is more than similarity," he wrote. "It is a kinship between the two, an agreement not merely of the effects, but also perhaps of the causes." In turn, engineers who designed telegraph networks, such as Samuel Morse and Werner von Siemens, looked to the biological nervous system as a model of centralization and organization. With people traveling across countries for the first time and communicating with one another across the world, interconnectedness became a social ideal. When Germany finally unified in 1871, its telegraph network, centered in Berlin and reaching all its territories, became both a symbol and an instrument of imperial power. Around that time, perhaps influenced by the predominant metaphor, German anatomist Joseph von Gerlach looked at nervous tissue through his microscope and saw the tangle of fibers—a reticulum.

Cajal, who grew up in the preindustrial countryside, saw in the nervous system the natural images of his childhood. "Is there in our parks any tree more elegant and leafy than the Purkinje corpuscle of the cerebellum or the psychic cell, in other words, the famous cerebral pyramid?" he asked. He observed branchlets of axons "in the manner of moss or brambles on a wall," oftentimes supported by "a short, delicate stem like a flower"; a year later he settled on the term "mossy fibers." These fibers, he found, end in "rosettes" that approach the dendrites of other cells but, again, do not touch them. There are "nest endings" and "climbing fibers," which cling "like ivy or vines to the trunk of a tree."

Above all, the cells seemed to connect like "a forest of outstretched trees." Gray matter was an "orchard"; pyramidal cells were packed into an "inextricable grove." Cajal hit on the embryological method for studying the nervous system, he said, while reflecting on the difference in complexity between the "full-grown forest" and the "young wood." The cerebral cortex, impenetrable and wild, was a "terrifying jungle," as intimidating as the one in Cuba, where he had fought in the Ten Years' War. By force of will, Cajal believed, human beings can transform "the tangled jungle of nerve cells" into "an orderly and delightful garden." Cajal always feared that the backwardness of his environment had stunted his intellectual growth. "I regret that I did not first see the light in a great city," he wrote in his autobiography. But the undeveloped landscape of his childhood became the rich ground that nourished an understanding that was distinct from that of his contemporaries.

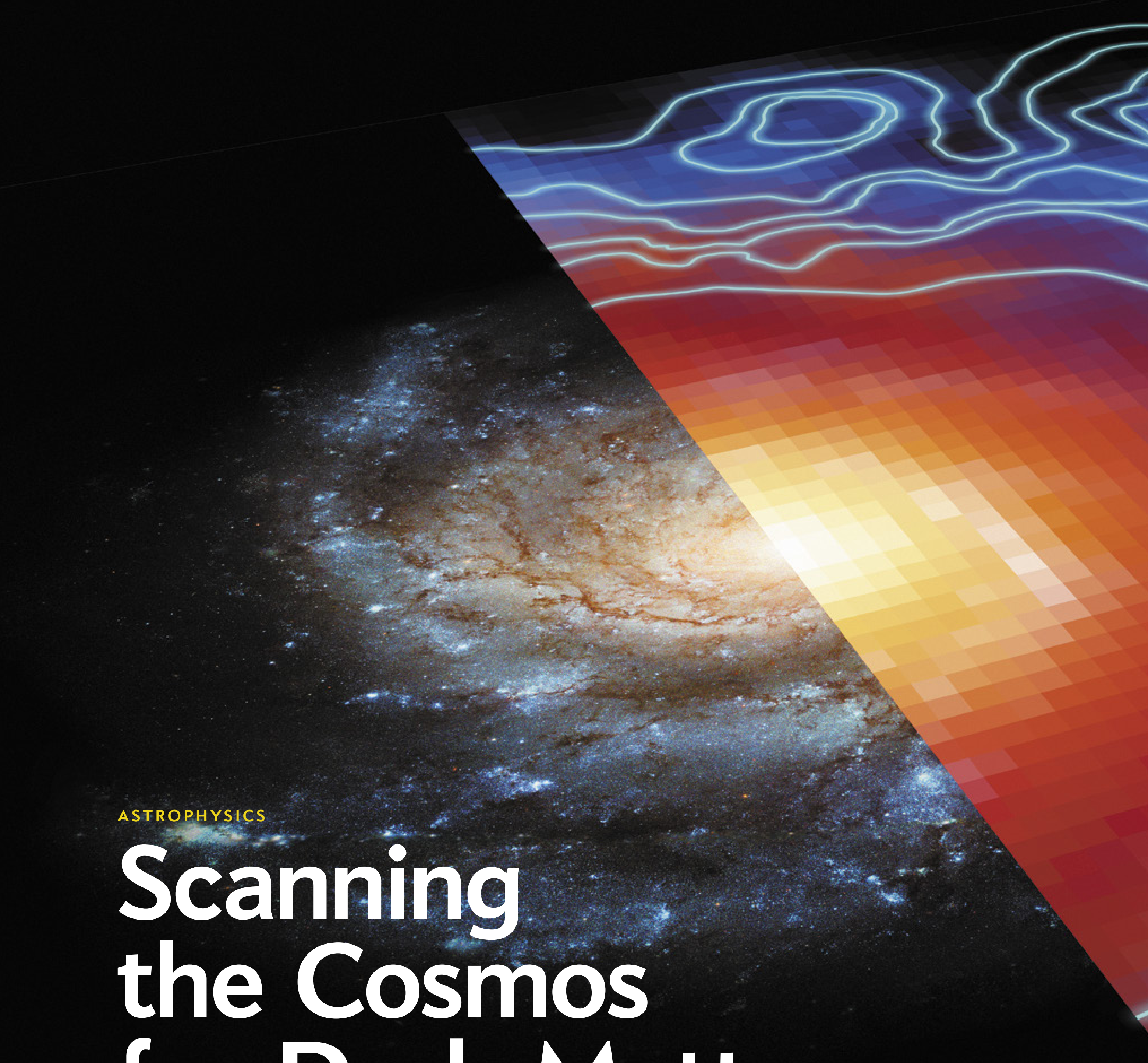
Although he evoked the telegraph from time to time, in an address written by him and read in his absence at the 1894 International Medical Congress in Rome, Cajal fundamentally rejected the metaphor. His opposition was rooted in both his anatomical findings and his observations of his own mind. "A continuous preestablished net—like the lattice of telegraphic wires in which no new stations or new lines can be created—somehow rigid, immutable, incapable of being modified," he said, "goes against the concept that we all hold of the organ of thought: that within certain limits, it is malleable and capable of being perfected by means of well-directed mental gymnastics." He knew, in other words, that he could change his own mind. That was why he could not tolerate the reticulum, whose structure was fixed. The nervous system must have the capacity to change, and that capacity, he argued, is crucial to an organism's survival. Cajal relied on a variety of terms to express this concept: "dynamism," "force of internal differentiation," "adaptation [of neurons] to the conditions of the environment"—and, most consequentially, "plasticity."

Cajal was not the first to use the term "plasticity," although his Rome address, delivered before a broad international audience, was probably responsible for its popularization. The concept remains one of Cajal's most enduring contributions to science, inspired by his unique and unconventional worldview. SA

FROM OUR ARCHIVES

The Art of Neuroscience. Sarah Chodosh and Liz Tormes; *Scientific American Mind*, November 2016.

scientificamerican.com/magazine/sa



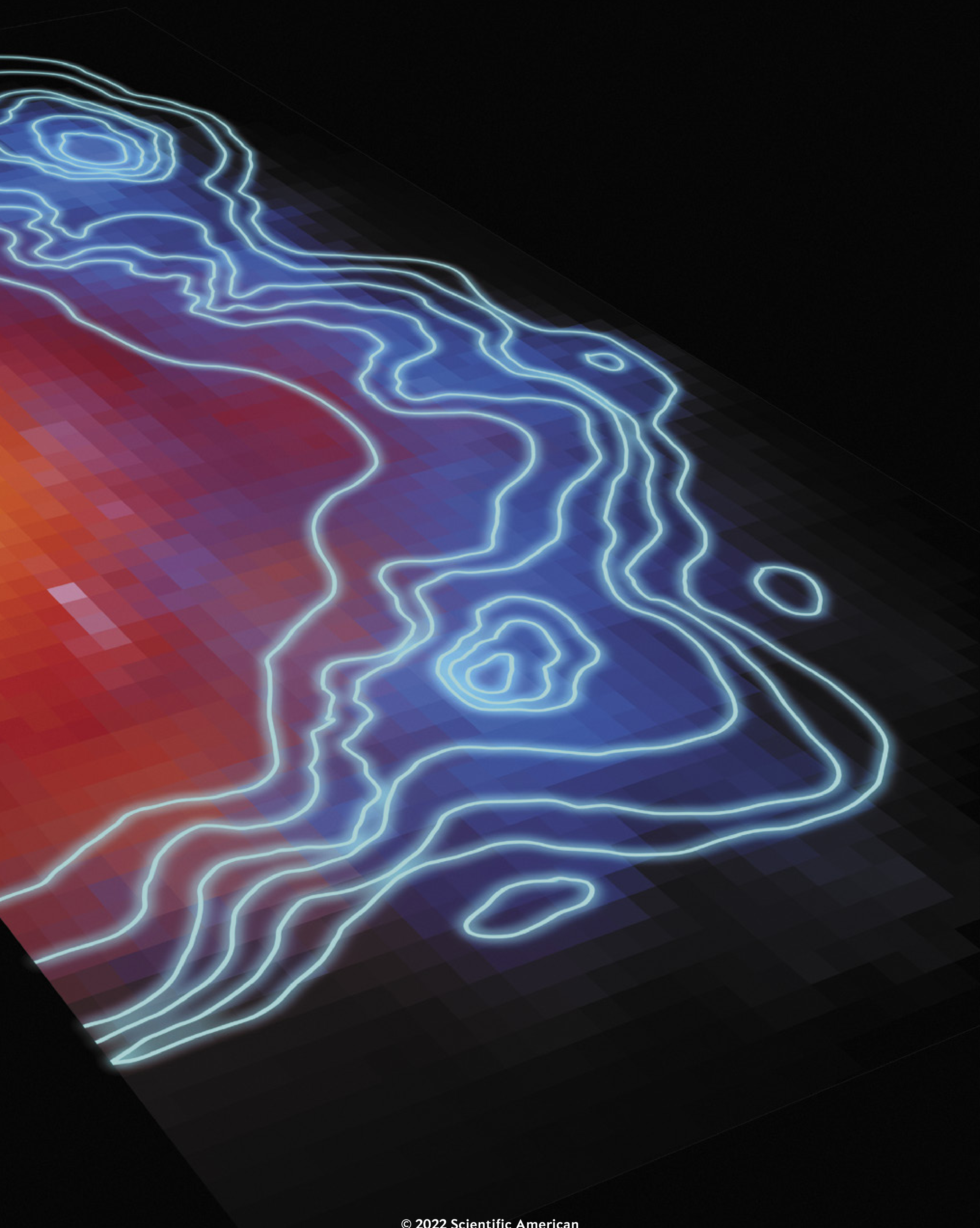
ASTROPHYSICS

Scanning the Cosmos for Dark Matter

Signals from space may point the way to the universe's hidden realm

By Chanda Prescod-Weinstein

Illustration by Mondolithic Studios



Chanda Prescod-Weinstein is a theoretical physicist. She is an assistant professor of physics and a core faculty member in women's and gender studies at the University of New Hampshire. She is author of *The Disordered Cosmos: A Journey into Dark Matter, Spacetime, and Dreams Deferred* (Bold Type Books, 2021).

HOW DO YOU THINK THE DARK MATTER PROBLEM IS SOLVED?” VERA C. RUBIN URGENTLY asked me, within minutes of being introduced at a 2009 Women in Astronomy conference. To this day, I can't remember what I said in response. I was awestruck: the famed astronomer who had won the National Medal of Science for her work finding the first conclusive evidence for dark matter's existence was asking *me,* a twentysomething Ph.D. student, for my opinion. I am certain that whatever I came up with was not very good because it was a problem that I had, until that moment, given no serious thought to. Until Rubin asked me my opinion, it had never occurred to me that I was entitled to have an opinion on the question at all.

If I disappointed her with my answer, she didn't show it. Instead she asked me to sit down to lunch with her and some other women astronomers, including former NASA administrator Nancy Grace Roman. Rubin then proceeded to fangirl over Roman, who is often referred to as “the mother of the Hubble Space Telescope.” It was quite a moment for me, to watch an elderly woman who had uncovered one of the greatest scientific mysteries of our time excitedly introduce us to her own hero.

Rubin cemented her legacy in the 1960s, when she studied stars inside galaxies and found something odd: stars on the outskirts of galaxies were moving faster than they were supposed to, as if there was an invisible matter there contributing a gravitational pull. Her work echoed findings from galaxy cluster studies in the early 1930s by Fritz Zwicky, which had led him to suggest the existence of *Dunkle Materie,* German for “dark matter.” Throughout the 1970s Rubin and astronomer Kent Ford published data consistent with this conclusion, and by the early 1980s scientists were in widespread agreement that physics had a dark matter problem.

Most attempts to track down dark matter in the laboratory have fallen into three categories. So-called direct detection experiments look for evidence of dark matter particles interacting with particles of normal matter—for instance, the element xenon—through one of the nongravitational fundamental forces, the weak force, as well as through hypothesized new forces. Collider experiments, such as those at the Large Hadron Collider near Geneva, take the opposite approach, smashing two regular particles together with the hope of producing dark matter particles. Meanwhile “indirect detection” experiments look for evidence of dark matter interacting with itself, with the resulting collision producing observable particles.

So far none of these strategies has turned up the missing matter. We still don't know if dark matter can talk to regular matter in any way beyond gravity. It may be impossible to produce in the accelerators we can build or to detect in the experiments we can construct. For this reason, astronomical observations—cosmic probes of dark matter—are one of our best hopes. These probes allow us to look for signatures of dark matter in environments that are difficult for us to produce on Earth—for example, inside neutron stars. More broadly, such searches look at dark matter's behavior under gravity in a variety of locations.

Despite the promise of this approach for studying dark matter, it has sometimes been caught in the middle between the astronomy and physics communities. Physicists tend to emphasize colliders and laboratory experiments and don't always prioritize links to astrophysical work. Astronomers tend to write dark matter off as a particle physics problem. This disconnect has implications for funding. In 2022 we have an opportunity to change that. The start of the 2020s marked the beginning of an important process known as the Snowmass Particle Physics Community Planning Exercise. This project, which takes place about once a decade, brings physicists together to explain prospective scien-

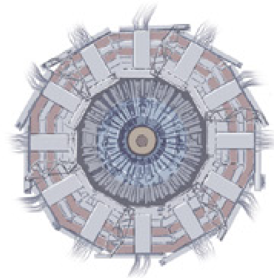
The Dark Matter Hunt

Scientists know the matter we can see is not all that is there. But so far attempts to find dark matter and discover its identity have not been successful. The search continues.

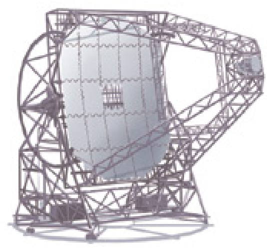
FOUR WAYS TO LOOK FOR DARK MATTER

Direct detection experiments, such as the Xenon1T detector in Italy, look for signs of dark matter particles interacting via the weak force with regular matter. Particle colliders, such as the Large Hadron Collider near Geneva, search for dark matter particles among the debris created when normal particles smash together. Indirect detection experiments, including astrophysical searches such as the High Energy Stereoscopic System (HESS) in Namibia, look for signs of dark matter interacting with itself, producing normal matter in the process. Indirect detections often involve looking for the aftermath of cosmic particles interacting with the atmosphere. All of these methods require dark matter to interact with traditional particles in some way besides gravity. If it does not, observations of astrophysical objects may be the only way to find the hidden material.

DIRECT DETECTION EXPERIMENTS

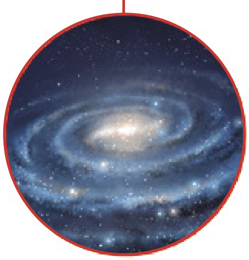


PARTICLE COLLIDERS

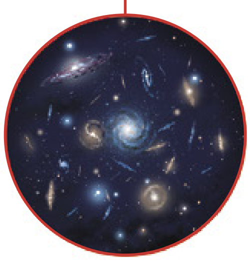


INDIRECT DETECTION EXPERIMENTS

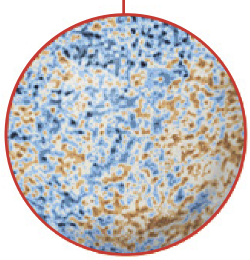
ASTROPHYSICAL SIGNALS



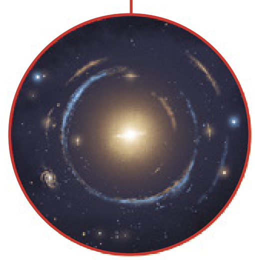
Centers of Galaxies
If dark matter is its own antiparticle—a possibility under the weakly interacting massive particle (WIMP) model—it would annihilate itself at the centers of galaxies to create an excess of gamma rays that telescopes could see.



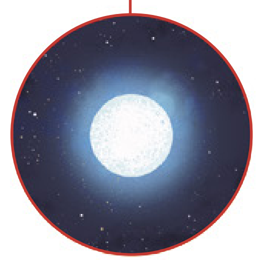
Galaxy Clusters
The same phenomenon—WIMP particles destroying themselves—could be evident in clusters of galaxies, where dark matter is also expected to be concentrated.



The CMB
The cosmic microwave background (CMB) is ancient light that pervades the universe. Patterns in the frequency of this light reflect how much total mass was present in the early cosmos, constraining different dark matter candidates.



Gravitational Lensing
Scientists can look at how mass bends light as it travels through the universe—a phenomenon known as gravitational lensing—to study how much mass dark matter contributes and what it might be made of.



Neutron Stars
These dense spinning stars may produce axions—one dark matter candidate—inside their cores. If so, the axions could decay into photons telescopes could see. They would also cause neutron stars to lose heat in a measurable way.

tific projects to a congressionally mandated panel that will determine scientific priorities. For the first time, cosmic probes of dark matter will be a distinct topic of consideration. Although Snowmass does not make formal policy recommendations, it is certainly the case that at each stage of the organizational hierarchy, there will be decisions about what science to emphasize.

A UNIVERSE OF DARK MATTER CANDIDATES

THERE IS STILL MUCH we don't know about dark matter, but we have come a long way since Rubin's work in the 1970s and 1980s. We now have good evidence to suggest that every galaxy lives in its own bubble of dark matter—called a dark matter halo—that extends well beyond the visible part of the galaxy. The amount of dark matter in

Graphic by Matthew Twombly

these galaxy-halo systems surpasses the amount of matter in the stars and planets and gas. In other words, all the particles that we have been able to identify in labs and colliders—referred to collectively as the Standard Model of particle physics—contribute only about 20 percent of the normally gravitating matter in the universe. If we take into account dark energy and the fact that matter and energy are fundamentally equivalent, we are down to understanding only about 4 percent of the cosmos. The Standard Model is both a stunning achievement and a theory that is, apparently, deeply incomplete.

Cosmic probes allow us to look for signatures of dark matter in environments that are difficult for us to produce on Earth—for example, inside neutron stars.

We need a new particle or particles to solve the problem.

Physicists now have an assortment of dark matter candidates. Most scientists favor candidates that are "cold dark matter"—particles that move relatively slowly (meaning, at nonrelativistic speeds much slower than that of light). Within the class of cold dark matter, one of the classic models is the weakly interacting massive particle (WIMP). Scientists presume that WIMPs would have formed naturally in the early universe and predict that they have some kind of interaction with regular matter through the weak force. The most popular WIMP models fall into a category of particles called fermions—a class that includes electrons and quarks.

WIMPs were the most highly favored dark matter candidates for a long time, particularly in the U.S. Opinions have shifted in recent years, though, as evidence for WIMPs has failed to show up at the Large Hadron Collider or in any of the direct and indirect detection experiments.

Recently the particle physics community has become excited about another hypothetical dark matter candidate: an axion. Axions are predicted to have smaller masses than WIMPs, and they are not fermions. Instead axions belong to a class of particles called bosons—the category that includes photons, or particles of light. As bosons, axions have fundamentally different properties than WIMPs, which opens the door to an intriguing possibility about the structures they could form. Axions are what first drew me into the world of dark matter research.

ALLURING ALTERNATIVES TO WIMPS

FIVE YEARS PASSED between my conversation with Vera Rubin and my first attempt at answering the question she had put to me. By then it was 2014, and I was a Dr. Martin Luther King, Jr., postdoctoral fellow at the Massachusetts Institute of Technology, appointed first to the Kavli Institute for Astrophysics and Space Research and then the Center for Theoretical Physics (CTP) and looking for something interesting to work on. It was there that Mark Hertzberg—at the time also a postdoctoral researcher at CTP—and I first started talking about a debate that had erupted among physicists: Could axions form an exotic state known from atomic physics called a Bose-Einstein condensate?

This possibility arises from a fundamental difference between bosons and fermions. Fermions must obey the Pauli exclusion principle, which means two fermions cannot share the same quantum state. This rule is why electron orbitals in chemistry can be so complicated: because the electrons orbiting an atom cannot occupy the same quantum state, they must spread out in different patterns with different amounts of energy called orbitals. Axions, on the other hand, can share a quantum state. This means that when we cool them enough they can all enter the same low-energy state and act collectively like one superparticle—a Bose-Einstein condensate. The possibility that this could happen naturally in space is, in my view, quite exciting.

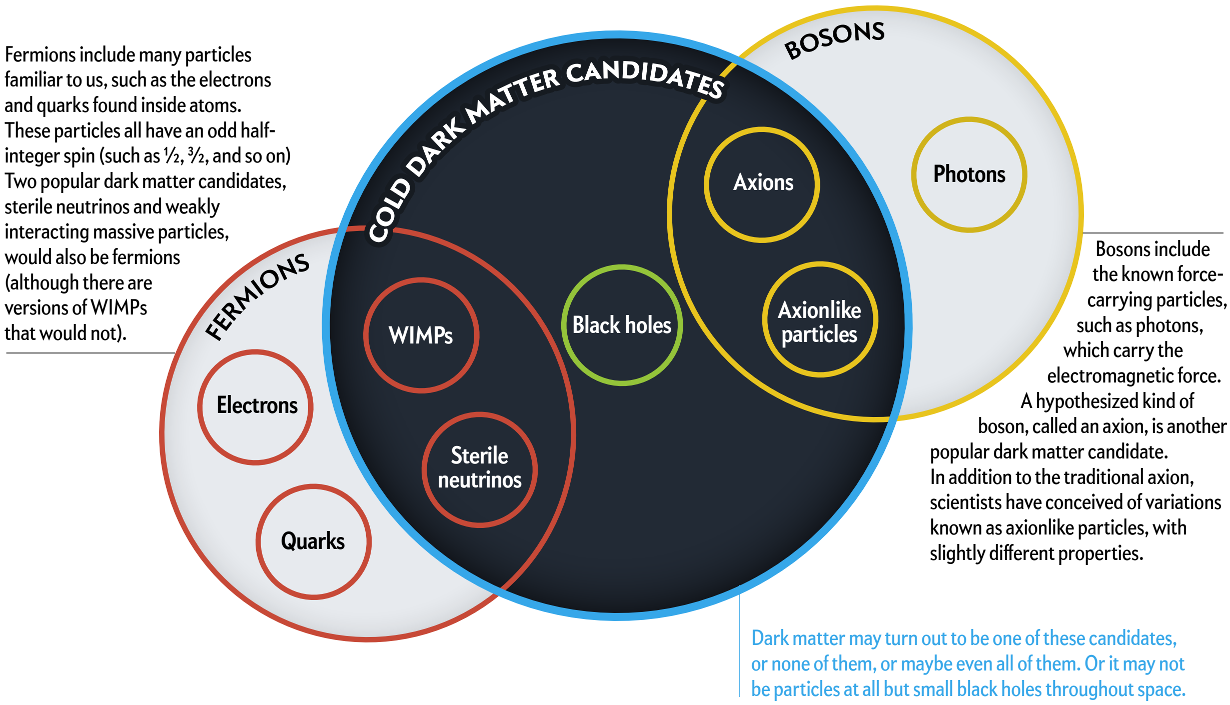
Axions had been proposed in the 1970s by Hertzberg's Ph.D. adviser at M.I.T., Frank Wilczek, one of the first to realize that one consequence of a model proposed by Helen Quinn and the late Roberto Peccei was a particle, which Wilczek named "axion" after a brand of laundry detergent. Thus, Hertzberg was already quite familiar with axions. I, on the other hand, was relatively new to this idea. I had spent most of my career focused on other questions, and I had to get up to speed. Along the way, I learned to distinguish between the traditional axion and the class of particles that physicists have come to loosely refer to as axionlike particles.

The traditional axion arises from the Peccei-Quinn extension to the theory of quantum chromodynamics (QCD), which describes another of the four fundamental forces, the strong force. Although QCD is a highly successful model, it also predicts phenomena we've never observed. Peccei and Quinn's work solves this problem, while providing a mechanism for producing dark matter. But another idea called string theory also proposes a series of particles with the same mathematical structure as the original axion; these particles have come to be called axionlike. The traditional QCD axion is usually expected to have a mass of about 10^{-35} kilogram—several orders of magnitude lighter than the electron—but the larger class of axions from string theory can be much lighter, down to 10^{-63} kilogram.

The work Hertzberg and I did together with our postdoctoral adviser Alan Guth led us to quibble with a popular view of how axions might form Bose-Einstein condensates. A distinguished physicist, Pierre Sikivie of the University of Florida, had prompted much excitement in 2009, when he proposed that QCD axions would form large condensates in the very early universe. His calculations suggested they would lead to ringlike galaxy halos rather than the spherical halos that most astronomers expect and that WIMP models predict. If so, then we might be able to tell what dark matter is made of just by looking at halo shapes.

Bosons or Fermions? Popular Dark Matter Categories

Scientists have a plethora of theories for what dark matter might be. Most suggest that the missing stuff is made of particles that have not been discovered yet. These fall into two categories—fermions and bosons.



But when Mark, Alan and I sat down to check how Sikivie's group had arrived at this prediction, we came to a radically different conclusion. Although we agreed that axion Bose-Einstein condensates would form in the early universe, they would be much smaller—the size of asteroids. Our model also did not give any indications, in the present-day universe, of what kind of axion structures we might find billions of years in the future. Trying to better model how—and whether—we get from small asteroid-sized condensates to the galactic-scale dark matter halos of today is still a significant computational challenge.

The same year our paper came out, another group was looking into other interesting implications of axionlike particles. A team led by Hsi-Yu Schive of National Taiwan University published computer simulations of certain axionlike particles that are often referred to as "ultralight axions" or "fuzzy dark matter," so named because they have a very low mass and would act like blurred-out waves rather than pointlike particles. They showed that these particles could form wavelike dark matter halos with Bose-Einstein condensates at their cores. Schive's paper generated new interest in ultralight axions and raised hopes that astrophysical observations could detect signs of the wavelike halo structures we expect.

These days axions and axionlike particles stand along with WIMPs as some of our best guesses at what dark matter could be. Another category that is growing in popularity is a model called self-interacting dark matter (SIDM). This idea predicts fermion dark matter particles that have some kind of interaction with one another—a self-interaction—beyond gravity. These self-interactions could create more interesting shapes and structures within a halo than a smooth, spherical blob. The particulars of the structures are hard to predict, though, and depend on the mass and other characteristics of the particles. Interestingly, axions may also interact with one another, though in different ways than self-interacting fermions.

There is an alternative to WIMPs, axions and SIDM: neutrinos. Although Standard Model neutrinos are now known to be too low in mass to explain all of the missing matter, these neutrinos are real and hard to see, making them functionally a small component of the dark matter that we call the cosmic neutrino background. In addition, a new type of neutrino has been hypothesized as a companion to the Standard Model

Graphic by Jen Christiansen

BULLET CLUSTER: Observations from the Chandra x-ray space telescope show the location of normal matter (*in pink*) as two galaxy clusters collide. Gravitational-lensing studies revealed the bulk of the mass (*in blue*) was separated from the normal matter, offering strong evidence for the existence of dark matter.

NASA/CXC/CfA/M. Markevitch (*x-ray*), NASA/STScI, Magellan/U. Arizona/ D. Clowe (*optical and lensing map*), ESO WFI (*lensing map*)

neutrino: the sterile neutrino. Sterile neutrinos are distinct because they interact primarily gravitationally and only mildly through Standard Model forces. In addition, they are perhaps the most popular warm—or at least somewhere between hot and cold—dark matter proposal.

Another idea that theorists are just starting to explore is that rather than a single dark matter particle, there may be an entire sector. Perhaps dark matter is made of traditional axions, axionlike particles, WIMPs, sterile neutrinos and SIDM—all together. One other tantalizing possibility is that dark matter actually comprises stellar-mass black holes that would have formed in the early universe. This option has become more popular since the 2017 detection of gravitational waves indicated that black holes in this mass range are more common than expected.

CLUES IN THE SKY

IN ASTRONOMY we are relatively passive observers. We can choose our instruments, but we cannot design a galaxy or a stellar process and watch it unfold. Cosmic phenomena rarely happen on human-friendly time scales—galaxy formation takes billions of years, and the cosmic processes that might emit dark matter particles do so over tens to hundreds of years.

Even so, astrophysical probes of dark matter can tell us a lot. For instance, the NASA Fermi Gamma-ray Space Telescope has functioned as a dark matter experiment by looking for gamma-ray signatures that could be explained only by dark matter. WIMPs, for instance, are predicted to be their own antimatter partners, meaning that if two WIMPs collided, they would annihilate each other just as matter and antimatter do on contact. These explosions should produce an abundance of gamma-ray light where there is dark matter, especially at the cores of galaxies where dark matter is densest.

In fact, the Fermi telescope does see an excess of gamma-ray light at the center of the Milky Way. These observations have inspired passionate debate among observers and theorists. One interpretation is that these fireworks result from dark matter colliding with itself. Another possibility is that the signal comes from neutron stars near the center of the Milky Way that emit gamma-ray light through the typical course of their lives. Some astrophysicists favor the more mundane neutron star explanation, but others think the signal is dark matter. The fact that there is disagreement is normal, and even I have a hard time deciding what I think. I am compelled by physicists Tracy Slatyer and Rebecca Leane's thoughtful research showing that a dark matter explanation is sensible, but in the end, only analysis of more detailed observations will persuade the community about either idea. Future data from the Fermi telescope and proposed experiments such as NASA's All-sky Medium Energy Gamma-ray Observatory eXplorer (AMEGO-X for short) have the potential to settle the debate.

Scientists have also used the Fermi telescope to look for evidence of axions. Theories predict that when axions encounter magnetic fields, they occasionally decay into photons. We hope that by looking over long distances, we might see signs of this light, offering proof that axions exist. And neutron stars—the potential confounding signal at the Milky Way's center—are actually a good place to look for dark matter on their own. Some theories suggest that these dense spinning stars produce axions when protons and neutrons collide in their cores. We might be able to observe these axions as they decay into photons and escape from the stars. And as neutron stars release the dark matter over tens to hundreds of years, they would cool down in a pattern that we may be able to measure—if we look long enough. Another hot topic of study right now is whether nonaxion dark matter collects in neutron stars, affecting the structure of the star. As a member of the NASA Neutron Star Interior Composition Explorer (NICER) collaboration, I am leading a research project that is using data from NICER, a little telescope on the International Space Station that is up for renewal later this year. Our project is looking for evidence that dark matter is inside or enveloping neutron stars.

We can also learn more about the nature of dark matter by studying the best evidence we have for its existence so far—the cosmic microwave background (CMB) radiation. This light is a radio signal that originated in the early universe, and it is inescapably everywhere, all around us. It provides a snapshot of a moment early in cosmic history, and the patterns we see in the frequencies of its light reflect the makeup of the universe when it was created. It turns out that we can only explain the patterns we see in the CMB by assuming that dark matter was present—if there were no dark matter, the CMB data would make no sense. The patterns in the data tell us what fraction of the total mass and energy dark matter contributed; they even help constrain the possible masses of the dark matter particles. As I write, the CMB-Stage 4 collaboration is preparing to use a collection of telescopes in Chile's Atacama Desert and at the South Pole to take the most detailed measurements yet of the CMB.

ON THE HORIZON

SINCE THAT 2009 Women in Astronomy conference, Rubin and Roman have both passed away, but their legacies live on through projects that will seek to better understand our universe. The NASA Nancy Grace Roman Space Telescope will launch in the mid-2020s, and although it is primarily focused on studying cosmic acceleration (the "dark energy problem") and exoplanets, it will also provide insight into dark matter. At the same time, here on Earth, the Vera C. Rubin Observatory in the Atacama Desert will support research on many questions, including the search for the dark matter that made Rubin famous.

In other words, we have lots to look forward to in the coming years. One reason is that almost any large-scale astronomical observation has something to tell us about dark matter. For example, a team in Mexico led in part by Alma X. Gonzalez-Morales and Luis Arturo Ureña-López showed that we can use the phenomenon of gravitational lensing, where large masses bend spacetime so much that it acts like a fun-house mirror, to place constraints on the mass of fuzzy dark matter. Gonzalez-Morales and Ureña-López are both active participants in the Rubin Observatory's Legacy Survey of Space and Time program, working on gravitational lensing and participating in the dark matter working group. Within the group, we are discussing observations that will capture more detailed information about dark matter halos that can then be compared with computer simulations of proposed dark matter candidates. Similarly, Roman telescope surveys of large-scale structure will provide insight into dark matter's behavior on cosmic scales.

In the future, proposed x-ray observatories such as the NASA Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X) can help us take a closer look at neutron star structure in ways that will enhance our understanding of dark matter's possible properties. Other proposed future projects such as NASA's All-sky Medium Energy Gamma-ray Observatory, or AMEGO (not to be mistaken for AMEGO-X), will do the same in a different wavelength.

Doing science is never just about calculations, observations and experiments; it is also about working collaboratively with other people, including policy makers.

I will be an active participant not just as a scientist but as one of three conveners, alongside Alex Drlica-Wagner and Hai-Bo Yu, for the Snowmass Cosmic Frontier's topic Dark Matter: Cosmic Probes. It is our responsibility to describe the excitement and possibilities of astrophysical searches for dark matter to the funding decision-makers. The document I will help produce may influence guidance that is given to the National Science Foundation and the U.S. Department of Energy about what research we conduct over the next decade.

Coincidentally, the astronomy community just recently completed a similar process known as the 2020 Decadal Survey on Astronomy and Astrophysics. The resulting report sidestepped substantively addressing the dark matter problem, but it still offered strong support for efforts to better map the CMB, instruments to study neutron stars and x-ray observatories—three goals that will help us understand dark matter.

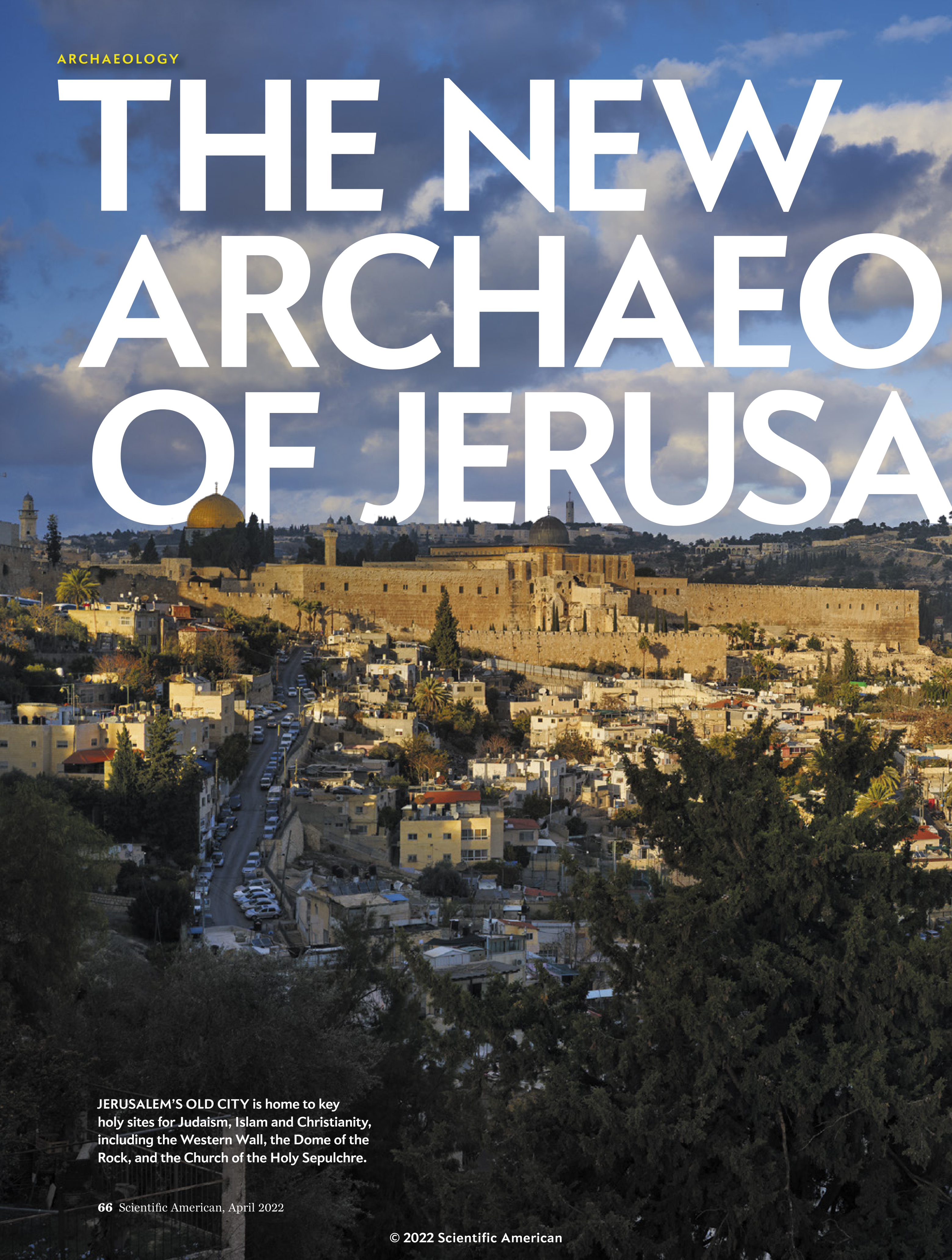
Doing science is never just about calculations, observations and experiments; it is also about working collaboratively with other people, including policy makers. How much progress we make will depend in part on what kind of support we get from lawmakers. Of course, this is stressful to think about. The good news is that there is a universe to wonder about, and trying to understand dark matter is a great distraction. SA

FROM OUR ARCHIVES

Dark Matter's Last Stand. Clara Moskowitz; April 2021.

scientificamerican.com/magazine/sa

THE NEW ARCHAEO OF JERUSA



JERUSALEM'S OLD CITY is home to key holy sites for Judaism, Islam and Christianity, including the Western Wall, the Dome of the Rock, and the Church of the Holy Sepulchre.

LOGY LEM

Even as biblical archaeology gets a high-tech makeover, a new generation of scholars remain haunted by ancient scripture and riven by modern politics

By Andrew Lawler

Andrew Lawler is a contributing writer for *Science* and a contributing editor for *Archaeology.* His latest book is *Under Jerusalem: The Buried History of the World's Most Contested City* (Doubleday, 2021). Read more at www.andrewlawler.com

LAST FALL THE DISCOVERY OF A 2,700-YEAR-OLD TOILET MADE HEADLINES AROUND THE WORLD. Its significance had less to do with long-ago plumbing than with the site of its discovery: Jerusalem. No place on Earth has seen so much digging for so long as this ancient Middle Eastern city; on any given day, a dozen or more excavations are underway in what is now a fast-growing metropolis. And no place attracts as much media attention for its archaeological finds, no matter how mundane. Only here would an ancient latrine seize the imaginations of millions.

Since the 1830s treasure hunters, religious enthusiasts and scholars have flocked here to dig into the past of a place billions of people hold sacred. Seeking tombs and riches, the early arrivals created the field of biblical archaeology—the only discipline founded on the idea that the tools of science can bolster rather than undermine traditional faith. In time, they were largely replaced by secular academics who were less devoted to upholding scripture or finding treasure but who nonetheless considered the Bible to be a tool as valuable as their spades.

Yet despite more than a century and a half of study, Jerusalem has largely confounded researchers. Entire eras within its 5,000-year-long archaeological record were missing, from the chapters documenting its early Judean roots to the later periods of Persian, Hellenistic and Arab dominance. Scientists knew little about the health of the city's inhabitants, what they ate, who they traded with, or how they influenced—and were influenced by—their neighbors.

The major culprit for these gaps in knowledge is the old fixation by archaeologists on Hebrew scripture at the expense of modernizing their approach to reconstructing the past. Only very recently have they adopted techniques such as radiocarbon dating, long considered standard practice by researchers working in other parts of the world. Intent on finding storied remains of the biblical era, they have been slow to undertake the arduous work of sifting through garbage heaps to gain a fuller picture of everyday life millennia ago.

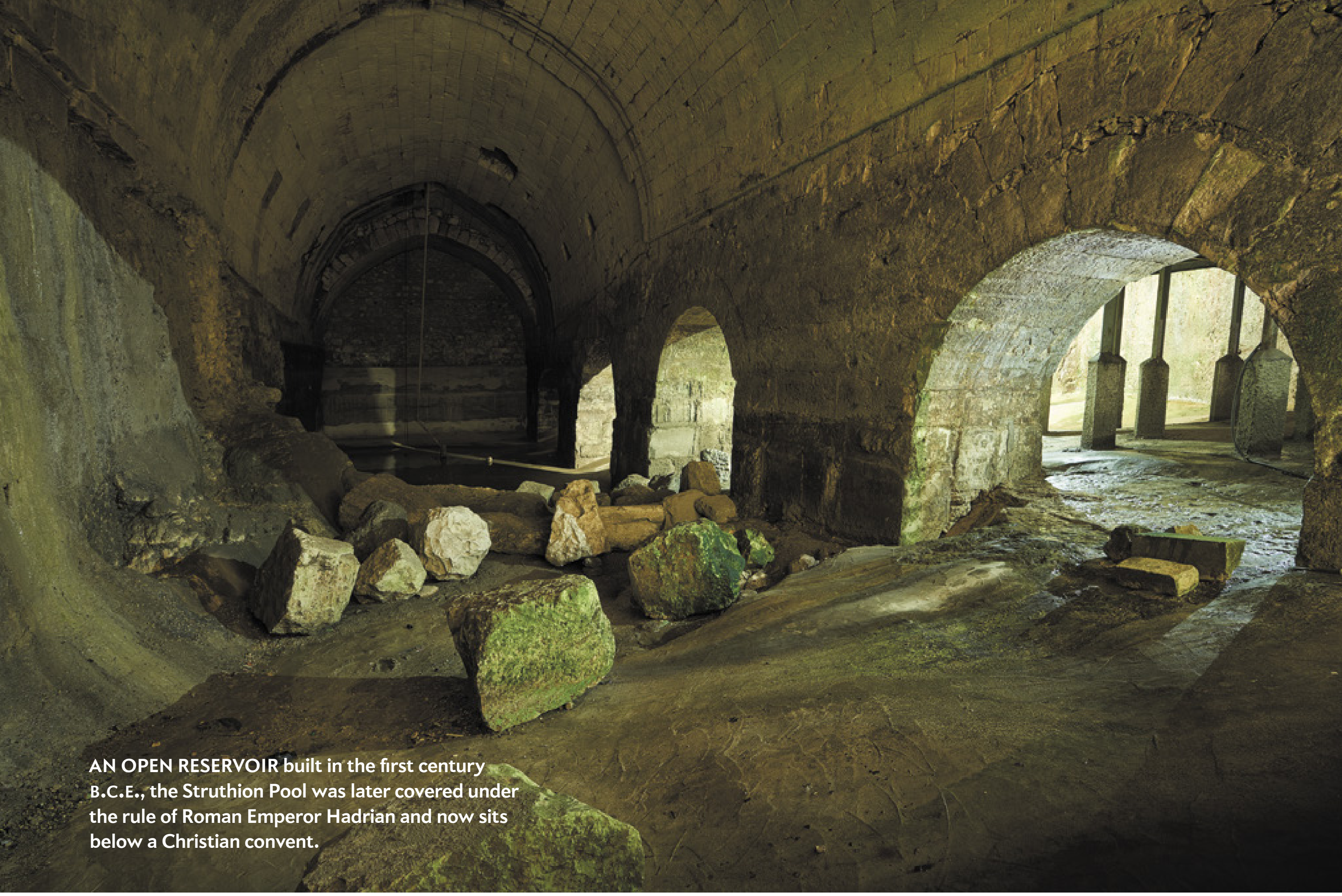
Now Jerusalem scholars are racing to catch up with their colleagues by embracing new analytical methods and goals. Yet 21st-century archaeology in a city shared by three faiths and contested by two peoples is as closely tied to religion and politics as it was in the 19th century—an arrangement that has cast a pall over the science. Excavations in Jerusalem today are firmly under the control of the Israel Antiquities Authority, a government organization that grants no permits to Palestinian teams in the city and only rarely approves them for foreigners. Fundamentalist Christian as well as Jewish groups with overt religious agendas pour money into costly digs. Israeli leaders regularly cite archaeological finds to strengthen their claim to the Holy City, whereas a host of international organizations denounce any excavations—no matter how impeccable the scientific method—in areas considered occupied.

"Truth springs up from the Earth," according to the part of the Bible that Christians and Jews call the Psalms and that Muslims call the Zabur. But the truth emerging from this city's past, revealed by the latest analytical techniques, is as complicated by the harsh realities of the present as it was when the first spade struck into the ground. This is what makes Jerusalem a uniquely challenging site for researchers. It is a rare crucible where religion, politics and science meet—sometimes to cooperate and sometimes to collide.

A DISTINGUISHED AMERICAN classical scholar named Edward Robinson started the biblical Gold Rush in the 1830s, at the dawn of modern archaeology. Robinson was a devoutly Protestant academic who believed in the Bible's inerrant truth. While on sabbatical in Germany, he encountered the new fashion of biblical criticism, which sought to apply logic and reason to scripture. Mortified by what he considered to be heretical questioning of the truth contained in the holy text, Robinson wanted to counter this growing tide of religious skepticism and secularism in the West. He would do this, he decided, by using scientific methods to show that the Bible accurately described real-world people, places and events. Armed with the Good Book as his field guide and a thermometer, measuring tape, telescope and three compasses as his tools, he set out for Jerusalem to find what he called "indisputable remains of Jewish antiquity."

Robinson began by attempting to tie the current-day names of

Simon Norfolk (*all photographs*)



AN OPEN RESERVOIR built in the first century B.C.E., the Struthion Pool was later covered under the rule of Roman Emperor Hadrian and now sits below a Christian convent.

villages, wells and streams in the region around Jerusalem to biblical texts to demonstrate the geographical accuracy of scripture. This marriage of data with faith proved irresistible to Western Christians. The book that he published in 1841 with his collaborator Eli Smith, bearing the weighty title of *Biblical Researches in Palestine and the Adjacent Regions,* proved an unlikely best seller on both sides of the Atlantic. With it, the men laid the foundation for "an entire new scholarly, religious, and political enterprise in the Holy Land," writes historian Neil Asher Silberman.

It was an enterprise that would reshape the Middle East. In 1863 the Ottoman sultan in Istanbul, who controlled Jerusalem and the surrounding region of Palestine, granted the city's first official dig permit to a French explorer and senator. The sultan was interested in neither the Bible nor science but in good relations with the senator's powerful confidante, Emperor Napoleon III. Soon, British, German and Russian teams gained their own permits and set out to measure, dig and analyze ancient sites across Palestine. This was not just pious poking into the past. The Ottoman Empire covered an immense swath of territory stretching from Eastern Europe to the Horn of Africa, and European powers competed fiercely to influence and dominate it. With its important Christian shrines, Jerusalem provided an easy access point for Europeans eager to gather intelligence and expand their sway within the empire. Diplomats, military officers and spies accompanied the biblical scholars, and many were eager to find treasure as well as expose the past.

Although Jerusalem has existed for 5,000 years, Westerners were focused on what might be called the city's biblical millennium, the era between the arrival of the Israelites after 1000 B.C.E. and the Roman destruction of C.E. 70, a period encompassing much of the action that takes place in both the Old and New Testaments. They were particularly drawn to the first centuries of Judean control of the city. Overwhelmingly Protestant, these explorers had grown up hearing about David's palace and Solomon's temple, as well as sacred and valuable objects associated with Judaism. These included the Ark of the Covenant, a gilded box said to hold the Ten Commandments brought down from Mount Sinai by Israelite leader Moses and reputed to have magical powers. In Jerusalem, the desires for knowledge, wealth and sanctity were hard to untangle.

From the start, excavators faced a unique set of challenges. Unlike many other ancient Middle Eastern sites, Jerusalem is not a layer cake of a mound, with the old remains below and the new above. Instead it was built on and from limestone, the product of a vast shallow sea that covered the region during the age of the dinosaurs. An ideal building material, Jerusalem's particular variety of limestone is relatively soft when quarried, then hardens and turns golden when left to weather. But complicating matters for archaeologists, a single stone hewn for an ancient Judean dwelling may have been reused by Romans for a temple, collected by Arabs to complete an arch and robbed by Crusaders to build a church. Given the dearth of wood and other organic materials used in construction, modern dating methods such as dendrochronology and radiocarbon, which rely on such materials, can be of limited use for determining when any given structure was built—and by whom.

The unstable nature of the ground itself poses further difficul-

EXCAVATION in a former parking lot just south of the Old City reveals evidence from the sixth century B.C.E. to the early Muslim period a millennium later (*left*), including a gold earring from the Hellenistic era in the third century B.C.E. (*right*).

Ever since, excavations there have periodically prompted demonstrations, sparked bloody riots and set off international crises, with participants getting assaulted and chased by mobs. Archaeology in Jerusalem is not for the faint of heart.

ties for investigators. Naturally crumbly, limestone landscapes harbor subterranean caves and streams. In Jerusalem, millennia of quarrying and destruction have left behind tons of small chips. What seems like solid rock is actually a gravelly sediment called shingle that can turn liquid in an instant. "The shingle would suddenly burst in like water, burying our tools and sometimes partially our workmen," one British excavator complained in the 1860s. Archaeologists have been complaining ever since. As recently as 2018, a collapse brought down tons of rocky debris at one archaeological dig.

And then there are the threats from above. Unlike ancient sites such as Babylon in Iraq, Jerusalem remains a living city crammed with shrines that draw a constant stream of Jewish, Christian and Muslim pilgrims. Simply digging a hole can be viewed as an act of disrespect or outright aggression. When the French senator conducted the first legal excavation at a Jewish tomb there in 1863, there was an outcry in Jewish communities around the world. A few years later Muslims worried that British digs aimed to undermine the walls holding up the city's acropolis, what Jews call the Temple Mount and Muslims call the Haram al-Sharif. (This wasn't as outlandish a fear as it might sound, given that the expedition leader was using gunpowder to blast his way through the rock below.)

AT THE END OF WORLD WAR I, Ottoman rule gave way to control by the British, who in turn relinquished Palestine in 1948, leaving behind warring Jewish and Arab factions to battle for command of the region. In the aftermath, the new state of Israel's capital was in West Jerusalem. Jordanian forces controlled East Jerusalem, which included the Old City and most of the ancient sites and shrines. The power structures changed again in the Six-Day War of 1967, when Israel conquered East Jerusalem and incorporated it into its capital, although most nations still consider this area occupied territory.

For the first time, Jewish Israelis had a chance to probe underneath the city even as they reshaped it above. Unlike Robinson and his mostly Christian successors, this new generation of biblical archaeologists was overwhelmingly made up of agnostics and atheists with little interest in proving the truth of scripture. But they were also nationalists fascinated by the Jewish past and viewed the Bible as a foundational text of their new homeland. Benjamin Mazar, a famous archaeologist and president of Hebrew University in Jerusalem, was unapologetic about their bias. "Biblical archaeology was part of Zionist idealism," he said in a 1984 interview in *Biblical Archaeology Review*.

Mazar and his colleagues found luxurious villas, grand avenues and even the ancient world's most impressive pedestrian overpass, all dating to the era of King Herod the Great and his successors, who ruled Judea under Rome's authority in the century before and during the time of Jesus. When an internal civil war turned into an uprising against the empire, Roman legions destroyed Jerusalem in C.E. 70. These discoveries electrified the Jewish public by bringing to light physical evidence of the time when it was a famous and prosperous Jewish city. "Israeli archaeologists, professional and amateurs, are not merely digging for knowledge and objects, but for the reassurance of roots," wrote Israeli author Amos Elon in 1971. The finds also drew the attention of Israeli politicians, who were quick to cite the physical evidence to bolster their controversial claim to the Holy City.

Palestinians decried such excavations as twisting science for political purposes, favoring the Jewish past at the expense of the city's ancient Canaanite and later Christian and Muslim heritage. "We were put in the freezer for 2,000 years," says Nazmi Al Jubeh, a Palestinian archaeologist at Birzeit University, referring to the lack of emphasis on the two millennia following the Roman destruction. There were important exceptions, such as when Israeli archaeologist Meir Ben-Dov uncovered half a dozen huge palaces dated to the seventh century C.E., shortly after the arrival of Arab Muslims in the city, and the discovery of a major and long-lost Byzantine Christian church. Yet there is no disputing that the Jerusalem digs in the decade following the Six-Day War—and the media coverage accompanying the resulting finds—were weighted heavily to the Jewish past.

Meanwhile archaeologists in Europe and North America were embracing new research methods and technological advances. Rather than focusing on unearthing monumental buildings, museum-quality artifacts and evidence of long-dead kings, these excavators sought to know more about how ordinary people lived, what trade routes tied disparate peoples together and what shifts in material culture revealed about societal changes. Using new techniques, researchers could be far more precise in dating artifacts, and by sifting carefully through dirt, they could produce samples that cast light on diet, disease, commerce and ritual.

Researchers in Jerusalem remained deeply conservative in their approach to studying the past, however. The continued quest to find the city conquered by the Bible's King David and glorified by his son King Solomon after 1000 B.C.E.—still missing after more than a century of digging—took precedence over questions about diet and disease. Even those archaeological techniques in wide use elsewhere met with suspicion. Carbon 14 dating, for instance, was dismissed out of hand by researchers who contended that its margin of error allowed one to argue that the age of any given find was whatever one wanted it to be.

The matter came to a head in the 1990s, when Tel Aviv University archaeologist Israel Finkelstein attacked academic and biblical assumptions about the ages of sites around Israel, including Jerusalem. After analyzing pottery from around the region, he concluded that the archaeological "clock" previously used to date those materials was off by a century. That meant buildings dated to 950 B.C.E. actually were built around 850 B.C.E. This might seem an academic detail, but the implications were dramatic. Indeed, they stood to "change the entire understanding of the history of Israel," Finkelstein wrote.

The most dramatic implication was that Jerusalem had never been the large and glorious center of a brief empire ruled by a fabulously wealthy King Solomon, as detailed in the Bible. Although David and his famous son may have existed, Finkelstein and a growing number of scholars saw them instead more akin to tribal chieftains of a hilltop town.

This claim infuriated many of the more traditional excavators, including Mazar's granddaughter, the late Eilat Mazar. Like Robinson in the 1830s, she set out to counter what she saw as a kind of heresy. In 2005, while digging on the eastern side of a rocky spur of land south of the city's acropolis, Mazar uncovered what she claimed was probably the palace of King David. Finkelstein and others countered that her dating was faulty and that the structure might have been built by Canaanites—a mix of ethnic groups who inhabited the Levant 3,000 years ago—long before David was supposed to have lived.

FEW WERE PERSUADED by Mazar's interpretation, but the dispute had the effect of radically altering the way archaeologists in Jerusalem conducted fieldwork. The battle over the city's past shifted from interpreting biblical passages to arguing over hard data. Excavators began to sift through each bucket of dirt, meticulously counting fish bones, parsing seeds, and probing for tiny bits of clay that might have been stamped with an administrative seal that could reveal clues to the nature of trade and governance. At Tel Aviv University, Finkelstein pushed to set up facilities that could handle an array of archaeological analyses, from determining the nature of the residue in the bottom of a cup to studying latrine samples to understand what illnesses plagued inhabitants.

The showcase of that transformation is best seen at a former parking lot, located on the western side of the rocky spur of ridge where Mazar dug up her building. "The archaeological sciences are important tools that have been completely underused here in Jerusalem," Tel Aviv's Yuval Gadot says. Since 2017 he and Yiftah Shalev of the Israel Antiquities Authority have been busy working their way down through a city block–sized site that contains a rare cross section of Jerusalem from the sixth century B.C.E. until the first centuries of Arab Muslim control a millennium later.

In one case, the excavators used a novel technique that charts changes in Earth's geomagnetic field to determine the intensity and speed of destruction of some of the site's key structures. This approach demonstrated that the burning and collapse of a major administrative building from the sixth century B.C.E. was sudden, rather than the result of small conflagrations and decay. The evidence of this dramatic event clearly aligns with the destruction of the Judean city by Babylonian forces in 586 B.C.E., described in detail in the Bible.

Yet until recently, researchers' understanding of what took place in Jerusalem in the subsequent four centuries came almost entirely from scripture because archaeologists had failed to find much beyond a handful of potsherds from this time. That period extended from the rule of the Persian Empire—which conquered the Babylonians—to the Hellenistic successors of Alexander the Great, who in turn swallowed the Persian regime.

By applying modern archaeological research methods, the parking lot team has illuminated this largely unknown period. Meticulous sifting of the excavated sediments, for example, revealed the presence of tiny bat bones in the debris of the destroyed building, showing that the site was abandoned for a time before refugees crept back. The team also discovered that both before and after the 586 B.C.E. calamity, Judeans were importing fish from the Nile.

A NIGHTTIME sound and light show highlighting the ancient Judean past draws tourists to the City of David National Park, operated by a right-wing Jewish organization within a largely Arab neighborhood.

Those imports fell off much later, probably because warfare between competing Hellenistic kingdoms following the death of Alexander the Great in the fourth century B.C.E. disrupted trade links.

This level of detail was wholly missing from previous biblical archaeology. "When you can have a good control of stratigraphy, you can start dealing with food habits and things like this," Gadot says. "Now we can excavate a home, analyze a family's food habits and understand their connection with the wider world."

Biblical texts also paint an image of Judeans in this long era turning inward, focusing on their temple cult that revolved around a monotheistic deity and embracing strict dietary rules, as well as taboos on animal and human images. But analysis of artifacts from the parking lot paints a more nuanced picture. Boxwood from distant Anatolia showed that the city's trade links were quite extensive. And one Persian-period vessel with the face of an Egyptian deity, presumed to be an import brought by an Egyptian or Phoenician merchant, turned out to be fabricated in or near Jerusalem—a sign that non-Judeans made their home in the city and brought their own traditions with them.

Nor are dietary taboos as defining of Judeans as scholars once thought. A June 2021 paper in *Near Eastern Archaeology* detailed the discovery of an entire pig skeleton in what appears to be a Judean home, not far from the city's acropolis that once supported the Jewish temple. The researchers concluded that not only was pork consumed in the heart of the city but that "pigs were raised for this purpose in the capital of Judah." And although the parking lot dig is focused heavily on biblical times, researchers there also are studying a Roman and Byzantine villa and taking samples from an eighth-century C.E. Arab latrine to determine the nature of parasites that debilitated inhabitants.

The new science-heavy approach to archaeology means that less of the work is done in the trenches and more is done in labs such as those in the basement of Tel Aviv's archaeology department building. This effort is also far more international than in the past, when the vast bulk of team members were Israeli Jews. Now American and European graduate students participate in the investigations in larger numbers, providing Israeli researchers with important links to the outside world. Israeli archaeologists also have

partnered with the country's Weizmann Institute of Science in Rehovot to gather large numbers of radiocarbon samples to calibrate a more accurate chronology of Jerusalem's past.

But the upgrade to Jerusalem archaeology does little to change the controversy that accompanies every dig in and around the Old City. The parking lot effort prompted angry Arab homeowners to take the project to court amid charges that the excavation was endangering their homes that loom along two sides of the deep pit. And the pit itself will serve as the basement of a massive visitor's center owned and operated by a controversial right-wing Jewish organization dedicated to settling more Jews in the area. "The whole use of archaeology as a legitimizer of the state has become a hallmark of Netanyahu," says Tel Aviv's Raphael Greenberg, referring to the former long-reigning Israeli prime minister.

Gadot insists that "Jerusalem should be explored just like Athens and Rome." But unlike those two ancient capitals, this one remains at the heart of one of the world's most challenging—and violent—predicaments. Science-based archaeology may have arrived to stay, but the religion and politics that are part and parcel of any major excavation here remain largely unchanged. "No amount of sieving, sherd counting, text criticism or ancient DNA analysis can alter that equation," Greenberg says.

LAST MAY, EILAT MAZAR passed away, but the Bible continues to exert an enormous influence over excavations in Jerusalem and across Israel. As the recent toilet discovery demonstrates, any find related to Jerusalem's biblical millennium is sure to make its way into Israeli newspapers and Web sites and often into American and European outlets. This coverage, in turn, can elicit vital donations for excavations that are, particularly in Jerusalem, often complicated and expensive endeavors. Much of the support for Mazar's digs, for example, came from a New York Jewish philanthropist and an unaccredited Christian college in Oklahoma.

With Mazar's passing, Hebrew University's Yosef Garfinkel is taking up her biblical standard. Six weeks before Mazar's death, she called him to her bedside and asked him to continue her excavations at the City of David National Park where she found her putative palace. He remains unconvinced that she clinched her case but hopes to find the necessary evidence by restarting the dig in the near future.

Garfinkel just completed a series of excavations outside the city that he says uncovered Judean settlements dating to not long after 1000 B.C.E. "We found the historical kingdom of King David," he insists. "It had fortified cities, writing and administration." Finkelstein, for one, is unimpressed, noting that the settlements survived only a few decades and reveal nothing directly about the size or status of Jerusalem itself. In recent years he and his opponents had narrowed their differences over the dating of key sites in and around Jerusalem down to a few decades, but Garfinkel's work has revived the old fight over what the city looked like when the Israelites arrived.

The resurgence of what Finkelstein sees as a traditional form of biblical archaeology leaves him troubled. He wants to put Jerusalem in the wider context of a fluid ancient Middle East and set aside the fixation on proving the existence of this or that monarch. But "the wave of conservative scholarship is becoming stronger and stronger," he says. "It is not just Eilat Mazar and Yosi Garfinkel. It is quite depressing. We are losing the battle."

To combat this trend, Finkelstein launched a new archaeology program at the University of Haifa last fall that will emphasize cutting-edge science, international collaboration and museum studies with its own deep-pocketed supporters. "But of course," he adds, "the battle is bigger than archaeology." Israel, like the U.S., is an increasingly polarized place, and those divisions are reflected in research as well as in politics. Demonstrating the accuracy of the Bible is not simply a matter of academic debate but part of a larger culture war.

Palestinians remain largely on the sidelines. Al Jubeh, the Birzeit University archaeologist, pins the ultimate blame for their marginalization not on Jewish Zionists but on Western Christians such as Robinson who were obsessed with the Old Testament. As a result, "Jerusalem is the most excavated site in the world, and it has come to tell an Israeli story," he says. "I think in the end, however, there is only one narrative—the narrative of science."

In a world of alternative facts, it's a comforting thought. Yet separating science from the conflicts that cleave this city is clearly a task of biblical proportions. SA

FROM OUR ARCHIVES

Ancient Jerusalem. Kathleen M. Kenyon; July 1965.

scientificamerican.com/magazine/sa

THOMAS EDISON naps under a tree in 1921, while U.S. President Warren Harding (*seated, right*) reads a newspaper.


Everett Collection, Inc./Alamy Stock Photo

PSYCHOLOGY

Nap Like a Genius

Thomas Edison jolted himself from the edge of sleep to boost creativity. His method can work for the rest of us, research indicates

By Bret Stetka

Bret Stetka is a writer based in New York City and editorial director of Medscape Neurology (a subsidiary of WebMD). His work has appeared in *Wired,* NPR and the *Atlantic.* He graduated from the University of Virginia School of Medicine in 2005.

THOMAS EDISON WAS FAMOUSLY OPPOSED TO SLEEPING. IN AN 1889 INTERVIEW PUBLISHED IN *Scientific American,* the ever energetic inventor of the lightbulb claimed he never slept more than four hours a night. Sleep was, he thought, a waste of time.

Yet Edison may have relied on slumber to spur his creativity. The inventor is said to have napped while holding a ball in each hand, presuming that, as he fell asleep, the orbs would fall to the floor and wake him. This way he could remember the sorts of thoughts that come to us as we are nodding off, which we often do not recall.

Sleep researchers now suggest that Edison might have been on to something. A study published recently in *Science Advances* reports that we have a brief period of creativity and insight in the semilucid state that occurs just as we begin to drift into sleep, a sleep phase called N1, or nonrapid-eye-movement sleep stage 1. The findings imply that if we can harness that liminal haze between sleep and wakefulness—known as a hypnagogic state—we might recall our bright ideas more easily.

Inspired by Edison, Delphine Oudiette of the Paris Brain Institute and her colleagues presented 103 participants with mathematical problems that had a hidden rule that allowed them to be solved much faster. The 16 people who cracked the clue right away were then excluded from the study. The rest were given a 20-minute break period and asked to relax in a reclined position while holding a drinking glass in their right hand. If it fell, they were then asked to report what they had been thinking prior to letting go.

Throughout the break, subjects underwent polysomnography, a technology that monitors brain, eye and muscle activity to assess a person's state of wakefulness. This helped to determine which subjects were awake rather than in N1 or if they were in N2—the next, slightly deeper phase of our sleep.

After the break, the study subjects were presented with the math problems again. Those who had dozed into N1 were nearly three times more likely to crack the hidden rule as others who had stayed awake throughout the experiment—and nearly six times more likely to do so as people who had slipped into N2. This "eureka moment," as the authors call it, did not occur immediately. Rather it happened after many subsequent attempts to solve the math problem, which is consistent with previous research on insight and sleep.

It's less clear that Edison's technique of dropping objects to ward off deeper sleep works. Of the 63 subjects who dropped the glass as they drowsed, 26 did so after they had already passed through N1 sleep. Still, the findings suggest that we do have a creative window just before falling asleep.

Oudiette says that, like Edison, her personal experience with sleep inspired the study. "I've always had a lot of hypnagogic experiences, dreamlike experiences that have fascinated me for a long time," she says. "I was quite surprised that almost no scientists have studied this period in the past two decades."

A study published in 2018 found that a brief period of "awake quiescence," or quiet resting, increased the odds of discovering the same mathematical rule used in Oudiette's experiment. And psychologist Penny Lewis of Cardiff University in Wales suggests that both rapid-eye-movement (REM) sleep—the phase in which our eyes dart back and forth and most dreams occur—and non-REM sleep work together to encourage problem-solving.

Yet for the most part, Oudiette is not aware of any other research specifically looking at the influence of sleep onset on creativity. She does, however, point to plenty of historical examples of this phenomenon.

"Alexander the Great and [Albert] Einstein potentially used Edison's technique, or so the legend goes," she says. "And some of the dreams that have inspired great discoveries could be hypnagogic experiences rather than

RESTING in his laboratory in New Jersey, Edison took brief breaks from work. But the inventor did not want to spend much time asleep.

Ford Foundation

night dreams. One famous example is the chemist August Kekulé finding the ring structure of benzene after seeing a snake biting its own tail in a 'half-sleep' period when he was up working late." Surrealist painter Salvador Dalí also used a variation of Edison's method: he held a key over a metal plate as he went to sleep, which clanged to wake him as he dropped it, supposedly inspiring his artistic imagery.

"This study gives us simultaneous insight into consciousness and creativity," says Adam Haar Horowitz of the M.I.T. Media Lab, who has devised technology to interact with hypnagogic states but did not collaborate with Oudiette's team. "Importantly," he adds, "it's the kind of study that you can go ahead and try at home yourself. Grab a metal object, lie down, focus hard on a creative problem, and see what sort of eureka moments you can encounter."

For University of California, Santa Barbara, psychologist Jonathan Schooler, who also was not involved with the project, the study does not necessarily prove that just anyone will be able to mine their creativity during this early phase of somnolence. As he points out, "residing in the 'sweet zone' might have also simply refreshed the study participants, making it easier for them to solve the problem later." But Schooler acknowledges there may be something very solid in the study's findings. "The new results suggest there is a creative sleep sweet spot during which individuals are asleep enough to access otherwise inaccessible elements but not so far gone the material is lost," he says.

Despite its reputation as the brain's period of "shutting off," sleep is, neurologically speaking, an incredibly active process. Brain cells fire by the billions, help to reactivate and store memories, and, it seems, allow us to conjure our mental creations.

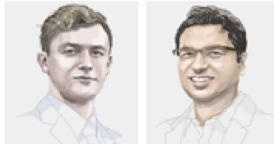
Oudiette hopes not only to confirm her findings in future research but also to determine if focusing on our hypnagogic state might help solve real-world tasks and problems by harnessing the creative potential of that liminal period between sleep and wakefulness. Additionally, she and her group are considering the potential of brain-computer interfaces to precisely identify brain-wave patterns associated with the onset of sleep, allowing the precise identification of when people should be woken up during their moments of putative insight.

"We could even teach people how to reach this creative state at will," Oudiette envisions. "Imagine playing sounds when people are reaching the right state and other sounds when they are going too far into sleep. Such a method could teach them how to recognize the creative state and how to reach it." SA

FROM OUR ARCHIVES

With Mr. Edison on the Eiffel Tower. R. H. Sherard; September 14, 1889.

scientificamerican.com/magazine/sa



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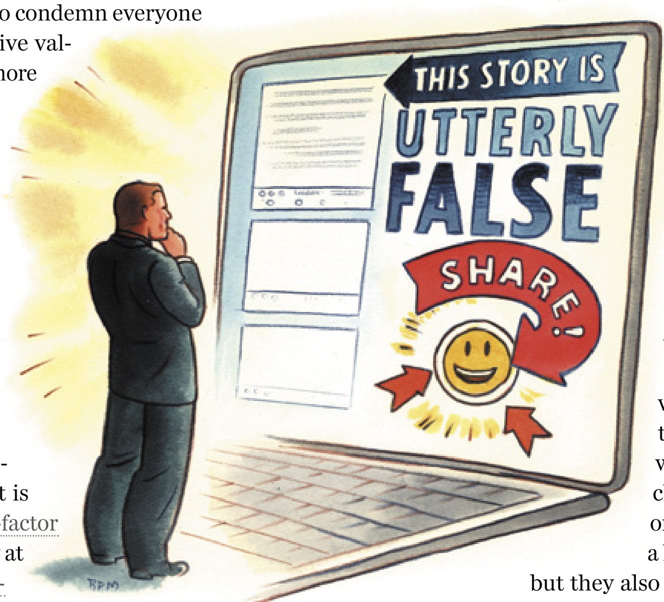
Fake-News Sharers

Highly impulsive people who lean conservative are most likely to pass along false news stories

By Asher Lawson and Hemant Kakkar

Behavioral and political scientists have pointed fingers at political conservatives, as opposed to liberals, when it comes to spreading fake news stories. But not all conservatives do it, and sweeping generalizations threaten to condemn everyone who subscribes to conservative values. This approach risks even more dangerous polarization.

Political leanings are far from the only determinants of behavior. Personality is a crucial influence, so our research on misinformation sharing has focused on that. One widely used psychological system for identifying personality traits organizes them into five categories: openness to experience, conscientiousness, extroversion, agreeableness and neuroticism. (It is called, unsurprisingly, the five-factor theory.) We looked specifically at conscientiousness, which captures differences in people's orderliness, impulse control, conventionality and reliability.



In a series of eight studies with a total of 4,642 participants, we examined whether low-conscientiousness conservatives (LCCs) disseminate more misinformation than other conservatives or low-conscientiousness liberals. First we determined people's political ideology and conscientiousness through assessments that asked participants about their values and behaviors. We then showed the same people a series of real and fake news stories relating to COVID and asked them to rate how accurate the stories were. We also asked whether they would consider sharing each story.

Both liberals and conservatives sometimes saw false stories as accurate. This error was likely driven in part by their *wanting* certain stories to be true because they aligned with their beliefs.

But actually sharing false news was markedly higher among LCCs compared with everyone else in the study, although some people of all persuasions did it. There was no difference between liberals and conservatives with high levels of conscientiousness. Low-conscientiousness liberals did not share more misinformation than their high-conscientiousness liberal counterparts.

What explains the exceptional tendency of LCCs to share fake news? To explore this question, we gathered information about participants' politics and personalities and administered questionnaires to assess their need for chaos—the desire to disrupt and destroy the existing political and social institutions—as well as their support of conservative issues, support for Donald Trump, trust in mainstream media and time spent on social media. LCCs, we learned, expressed a general desire for chaos, and this need may explain their proclivity to spread misinformation. Other factors, including support for Trump, were not as strongly related.

Unfortunately, our work on this personality trait also suggests that accuracy labels on news stories will not solve the problem of misinformation. We ran a study where we explicitly stated whether each news story in question was false, using a "disputed" tag commonly seen on social media, or true, using a "supported" tag. We found that the supported tag increased the rate at which real stories were shared among both liberals and conservatives. LCCs, however, continued to share misinformation at a greater rate despite the clear warnings that the stories were false.

We ran another study that involved explicitly telling participants that an article they wanted to share was inaccurate. People then had the chance to change their choice. Not only did LCCs still share fake news at a higher rate than others in the study, but they also were comparatively insensitive to direct warnings that the stories they wanted to share were false.

The poor effectiveness of warnings among LCCs is worrying because our research suggests these people are primary drivers of fake-news proliferation. Social media networks therefore need to find a different solution than just tagging stories with warning labels. Interventions based on the assumption that truth matters to readers may be inadequate. Another option might involve social media companies monitoring fake news that has the potential to hurt others, such as misinformation related to vaccines and elections, and actively removing such content from their platforms.

Whatever the case, until these companies find an approach that works, this problem will persist. In the interim, our society will pay the cost of spreading misinformation. The long, conspiratorial road that rioters followed to the January 2021 Capitol insurrection shows that this spread can have serious and damaging consequences. SA

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Illustration by Ross MacDonald

FICTION

Half-Lived Years

A sci-fi novel where the grief of pandemic stasis transcends time and space

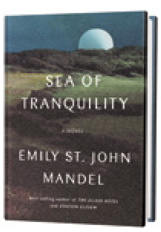
Review by Omar El Akkad

Peel away the speculative skin of Emily St. John Mandel's latest novel—the time travel, the moon colonies, the Möbius strip of a plot that, against all odds, holds together until the very last page—and what's left is something much more vulnerable: a story about grief. In this moment of unbearable negative space, of sputtering pandemic disruptions and mind-numbing stasis, Mandel has written a eulogy for our half-lived years.

Sea of Tranquility, which forms a loose triptych alongside Mandel's two most recent novels, *The Glass Hotel* and *Station Eleven,* opens with a scene of exile: It is 1912, and Edwin St. John St. Andrew, the recently banished son of a well-to-do British family, is "hauling the weight of his double-sainted name across the Atlantic by steamship." His destination is the eastern coast of Canada. He has no concrete plans, no real sense of purpose, and eventually he will find himself on the other side of the country, wandering through a forest in British Columbia, where, in a flash of weirdness, the first hints of this novel's true scope in space and time are revealed.

In subsequent chapters the narrative hops from Edwin's story to almost present-day New York City (where Mandel wrote this novel during the COVID pandemic, the sound of ambulance sirens surely at times a near-constant companion), then to a future moon colony, with multiple stops along the way. At first all that holds these disparate threads together is the sense that something is off, an almost imperceptible tear in the fabric of time. Eventually the threads begin crossing, and it becomes impossible not to keep reading to see how these story lines will converge.

The most visceral and immediate of the novel's narrative threads concerns a writer named Olive Llewellyn, who when we first meet her has temporarily left her family behind on one of the moon colonies to come to Earth for a book tour on the eve of a new global pandemic. To her credit, Mandel makes no effort at coyness—it is pretty clear that many of Olive's experiences mirror her own, from having to grind through countless bizarre interview questions ("What's your favorite alibi?" one interviewer enthusiastically asks Olive, as though we all carry one around in our back pocket in case of emergencies) to the crushing weight of days spent on the road and the simple desire to just go back home. These passages alone are worth the price of admission, not so much for voyeuristic extrapolation about how much of this book is really disguised memoir but rather for the pitch-perfect descriptions of the writing life, both before and during COVID.



Sea of Tranquility
by Emily St. John Mandel.
Knopf, 2022 ($25)

The past few months have seen the birth of what might be called the first full generation of pandemic-era novels—books such as Neal Stephenson's *Termination Shock,* Hanya Yanagihara's *To Paradise* and Sequoia Nagamatsu's *How High We Go in the Dark.* Whether these books were written before the COVID era or not, they are now destined to be read in the shadow of the present moment, just as any novel released between 2017 and 2021 that touched even tangentially on authoritarianism was inevitably read in the shadow of Trump.

In some cases, the plagues that haunt

Illustration by London Ladd

this new crop of books are little more than scenery, a kind of wry nod to the low-grade fear many of us have that maybe this is just what the future will look like: one vicious contagion after another. Sometimes they are a means to critique the maddening vulnerability of individual-centric societies struggling against calamities that require, more than anything, a communal response. In stories such as Lawrence Wright's *The End of October,* they are action-movie fodder: pathogens cast in the role of supervillains.

Emily St. John Mandel's characters might suffer from a great many maladies but none more unendurable than grayscale lives.

Mandel's work occupies the decidedly introspective end of this spectrum. As with her previous novels, there is no hard sci-fi in *Sea of Tranquility,* no detailed explanations of the biomechanics of disease or the physics of time travel. Occasionally a tracking device might make an appearance out of narrative necessity, or a character may briefly note the rules of the game before slipping through time, but all these descriptions are firmly subservient. It is the emotional and psychological consequences of these technologies and calamities with which the novel is chiefly concerned. When Olive sits on an airship with three masks over her face, terrified of bringing a new illness home to her husband and daughter, it is only tangential that the airship is traveling to the moon. When she trudges through yet another virtual lecture to a room full of holograms, every reader will be reminded of their last Zoom meeting and the vaguely dehumanizing sense of being ushered into a cheap facsimile of the world.

Many of Mandel's signature moves are here: the interweaving plotlines, the quietly dystopian setting and, of course, the deadly pandemic as narrative device. But perhaps more than all these things, the most common and powerful motif in Mandel's fiction is the adherence to the idea that art and beauty are necessary. Her characters might suffer from a great many maladies but none more soul-draining than aesthetic poverty, none more unendurable than grayscale lives.

Art seeps in through every seam of this story. As soon as Edwin arrives in Canada, he takes up painting classes. Violin notes echo through the centuries, as do the words of a novel within the novel. The work of Shakespeare makes a cameo, as it has before in Mandel's books. Art is the means by which characters decipher the secrets of their own existence, in some parts of the novel quite literally.

Perhaps this is why *Sea of Tranquility,* for all its narrative cleverness and sci-fi inventions, is at its core an emotionally devastating novel about human connection: what we are to one another—and what we should be.

Midway through the book a pandemic tears through the population, both on Earth and in the distant colonies, and several of Mandel's characters are forced into numbingly inward lives as depleted and fear-lacquered as so many of ours these past couple of years. It is the small details of this self-imposed cocooning, these hollowed-out moments, that cut deepest. The novel's most crushing scene, only a few lines long and told in passing, involves a young child deep into pandemic lockdown having a conversation with an inanimate object, trying to make friends. I have loved every one of Mandel's books (full disclosure: she was kind enough to blurb my first novel), but none has hit a nerve quite the way this one did.

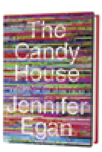
Despite this heaviness, *Sea of Tranquility* is a brisk read. At a line level, the verbs do much of the heavy lifting, and the overarching plot, which involves a vast time-travel bureaucracy, is deliciously and just a little disconcertingly addictive. There is constant movement both within scenes and in the grand sweep of the novel. As the pandemic rages still through the real world, some of the scenes will feel a little too close. But after so much time spent away from one another, after so much distancing, the closeness is in its own way a balm, a reminder that we were, even in our aloneness, together.

Omar El Akkad is a Canadian-Egyptian journalist and author of the novels *What Strange Paradise* (2021) and *American War* (2017).

IN BRIEF

The Candy House

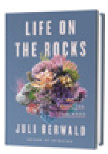
by Jennifer Egan.
Scribner, 2022 ($28)



Like its prequel, the 2011 Pulitzer-winning *A Visit from the Goon Squad,* Jennifer Egan's newest book reads not quite like a novel or a short story collection but like a fragmentary work of fiction with many perspectives and styles. This time a technology called Own Your Unconscious—a headset that lets people revisit their memories or see someone else's—is the conceit that brings old and new characters together in New York, Chicago, the American Southwest, and elsewhere as they navigate grief, love, parenthood, sex, addiction and trauma. Funny, heartfelt and cerebral, *The Candy House* asks compelling questions about authenticity and privacy in the era of surveillance capitalism. *—Adam Morgan*

Life on the Rocks: Building a Future for Coral Reefs

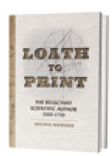
by Juli Berwald. Riverhead Books, 2022 ($28)



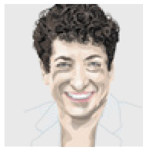
Ocean scientist Juli Berwald is adamant that *Life on the Rocks* is not an obituary. The threats to coral reefs are daunting and multilayered, but so, too, are the solutions. Berwald goes beyond the usual methods (preservation, reef-safe sunscreen) to describe unlikely efforts by special-ops veterans turned reef doctors, marine scientists and a conglomerate candy company. One idea involves nebulizing seawater into clouds over reefs to reflect more of the sun's radiation. Each highly readable chapter leans toward optimism, but key questions go unresolved. Are corals resilient enough to withstand warming oceans, or are these "success stories" death rattles in disguise? *—Maddie Bender*

Loath to Print: The Reluctant Scientific Author, 1500–1750

by Nicole Howard.
Johns Hopkins University Press, 2022 ($55)



The arrival of the printing press was a complicated milestone for scientific communication. Wary of intellectual-property theft, information overload and underprepared readers (Descartes decried "the cavils of ignorant contradiction-mongers"), early scientists sought to embrace print's possibilities while avoiding its pitfalls: Huygens published his discovery of Saturn's rings in an anagram; Galileo strategically distributed review copies of his work, elevating him to Medici court mathematician. History professor Nicole Howard's analysis offers startling glimpses behind the scenes of foundational scientific texts. *—Dana Dunham*



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).

Paths to a Less Silent Spring

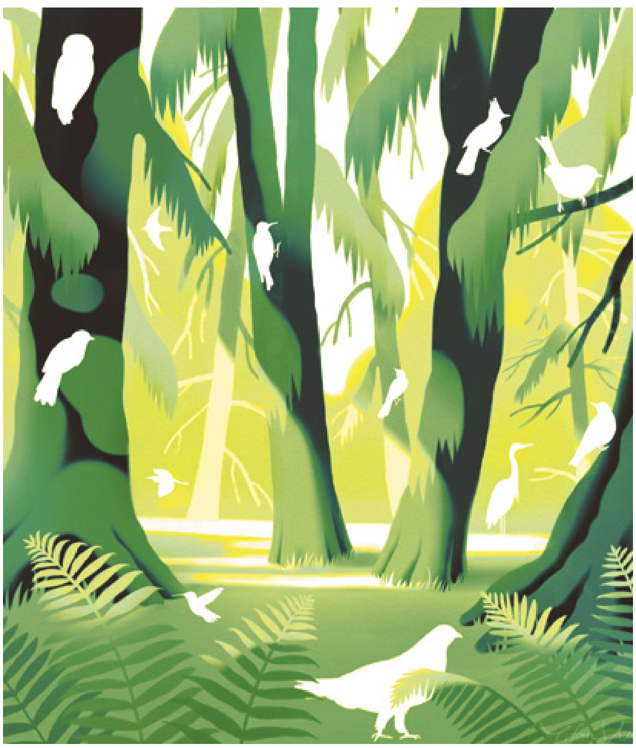
We can still act on Rachel Carson's pleas to save biodiversity

By Naomi Oreskes

Rachel Carson's classic best seller about ecological threats, *Silent Spring,* started a wave of American environmentalism. It played a direct role in the 1972 decision by the newly formed U.S. Environmental Protection Agency to ban use of the pesticide DDT. Ernest Gruening, one of the first two U.S. senators from Alaska, said Carson's writings had "altered the course of history." It will be 60 years ago this June that the public was introduced to Carson's arguments, as her book chapters were serialized in the *New Yorker* magazine. The coming anniversary makes this a good time to consider whether the book achieved one of her major goals: protecting wildlife and, in particular, birds.

Carson took a complex technical subject—the damaging effects of persistent pesticides—and expressed it in one simple, poetic image: a spring in which no birds sang. She asked us to imagine what it would be like to awaken in the morning to a world without these songs. She wrote with grace, and she made us feel the loss. But how well have we acted on Carson's warnings?

With some exceptions, we haven't been very successful, and neither have birds. In 2019 a major study, led by Cornell University ornithologist Kenneth V. Rosenberg, showed that 29 percent of North American birds have vanished since 1970. The study was notable because of its sweep: it integrated data across scores of species and the different biomes birds live in, and it used a variety of approaches to validate its counts; an article published by the Audubon Society called the result "a sobering picture" of widespread avian decline. Grasslands were the hardest hit, with a documented loss of more than 700 million breeding individuals—a decline of more than 50 percent. But major declines occurred in every biome save one and in nearly every species. The net toll amounted to nearly three billion individual birds, a figure that sparked a campaign with tips on what people can do to save them. (Top two: add decals to windows and keep cats inside.)



Given these data, it is tempting to conclude that despite the brilliance of her writing, Carson did not succeed in protecting birds. Moreover, the avian decline is part of a tremendous loss of global biodiversity driven by human activity. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), more than 40 percent of amphibian species, almost 33 percent of reef-forming corals and more than a third of all marine mammals are threatened. In all, biologists estimate that more than a million species are at risk. This also endangers human well-being, and the group notes that "we are eroding the very foundations of our economies, livelihoods, food security, health and quality of life worldwide."

Still, the 2019 bird study, despite its grim results, also suggests that protecting biodiversity (and thereby ourselves) is not a lost cause. One important exception in the otherwise bleak picture its scientists painted is wetlands (and the waterfowl that inhabit them). There bird abundance increased 13 percent. What distinguishes wetlands from other ecological areas? One answer is that wetlands have been especially shielded from excessive industrial activity for a long time. The areas have been under a host of legal protections on the federal, state and tribal level. Some of these laws, such as Massachusetts's powerful Wetlands Protection Act, prioritized wetlands for their diverse ecological value. Others safeguarded such areas because they are important to navigation and commerce, fisheries, flood control and water supplies. The 1899 Rivers and Harbors Appropriation Act, for instance, secured wetlands as parts of navigable waterways.

The other encouraging exception in the bird study was raptors, a group that includes the majestic bald eagle. Raptor numbers have increased by 15 million individuals. Bald eagles were on the verge of extinction at the time Carson wrote, but they recovered in large part as a result of the ban on DDT. A news story published by the Audubon Society notes that "the numbers show that taking steps like wildlife management, habitat restoration and political action can be effective to save species." Scientists have documented the current threat to biodiversity. Their data also show that if we act on this information, we can change the outcome. SA

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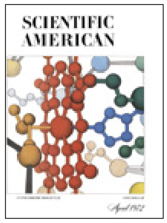
Illustration by Yifan Wu

Compiled by Mark Fischetti

APRIL

Your Ad Here

Although advertisements are meant to sell products, they can also provide insight into the state of science and technology at a given time. In 1872 lard oil was in demand for various uses. In 1922 consumers were eager for asbestos. What will people think 100 years from now about the goods and services being marketed today: credit cards, Facebook, smartphones that don't continuously assess all your bodily functions and cribs unable to teach babies multiple languages?



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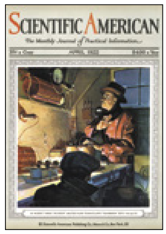

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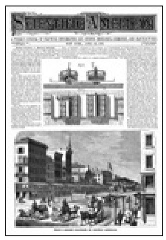

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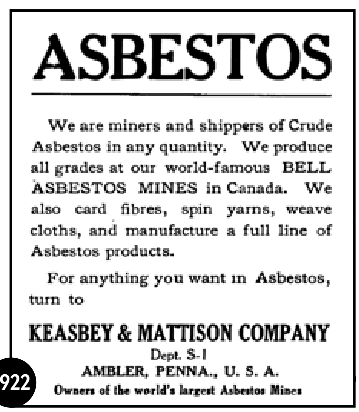
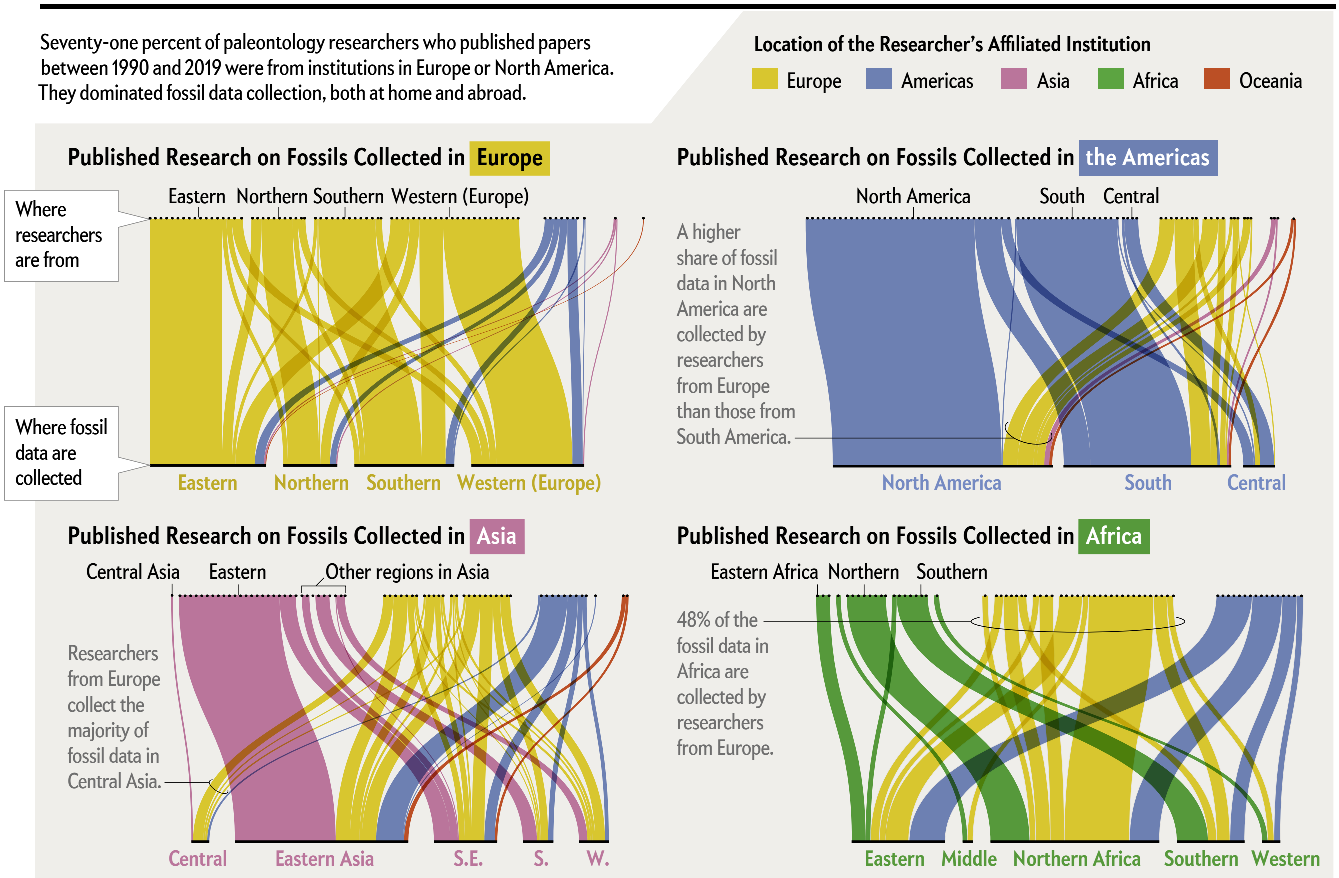


1922

Scientific American, Vol. XXVI, No. 16; April 13, 1872 (*lard oil*); *Scientific American*, Vol. 126, No. 4; April 1922 (*loudspeaker, asbestos, tires*); *Scientific American*, Vol. 226, No. 4; April 1972 (*car, slide rule*)

Text by Clara Moskowitz | Graphic by Youyou Zhou

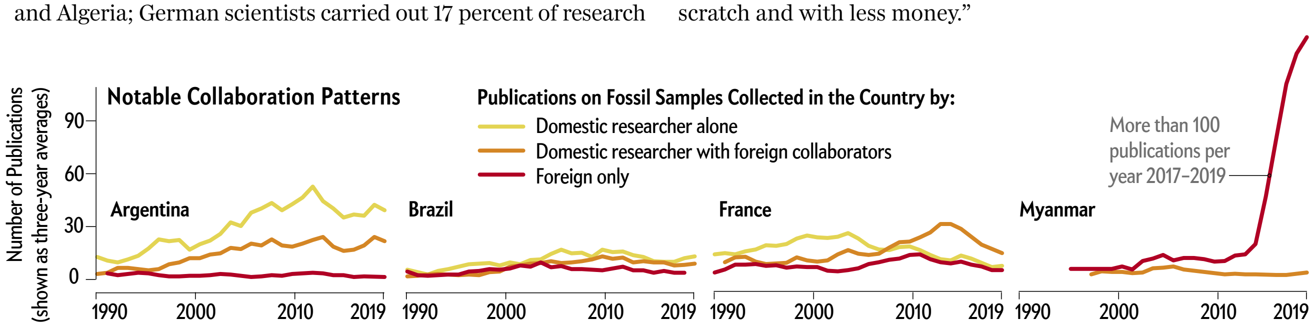


Colonialism Shadows Fossil Science

Paleontologists from a small number of countries control much of the world's fossil data

Rich countries overwhelmingly dominate paleontology research, even when the fossils do not originate there, a new study shows. Researchers analyzed 26,409 paleobiology papers from 1990 to 2020 and found that scientists in high- or upper-middle-income countries contributed to 97 percent of fossil research. And those from former colonial powers disproportionately controlled fossils from their former colonies. For example, French researchers conducted a quarter of all paleontology studies in Morocco, Tunisia and Algeria; German scientists carried out 17 percent of research on fossils from Tanzania; and 10 percent of studies on South African and Egyptian fossils were conducted by British investigators.

"This was very eye-opening," says Nussaïbah B. Raja-Schoob, a paleontologist at the Friedrich Alexander University of Erlangen–Nuremberg in Germany, who co-led the study, published in *Nature Ecology & Evolution*. "With colonialism, certain countries already had an advantage. After independence, the knowledge wasn't transferred back, so a lot of countries had to start from scratch and with less money."



Paleontology is a long-established discipline in Argentina and Brazil, the top two research destinations in South America, where most domestic research is carried out by local researchers. France, the chief research destination in Europe, has seen an increase in local research with foreign collaborators. There has been an increasing interest in fossils from Myanmar, especially organisms preserved in amber, from foreign researchers since 2015.

Source: "Colonial History and Global Economics Distort Our Understanding of Deep-Time Biodiversity," by Nussaïbah B. Raja et al., in *Nature Ecology & Evolution*; February 2022