SCIENTIFIC AMERICAN

Quantum Spacetime

New Hope for Pain Relief

Cleaning Up Greenhouse Gases

What Was It Like to Be a Dinosaur?

New insights into their senses, perceptions and behaviors

SEPTEMBER 2024
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SCIENTIFIC AMERICAN

FEATURES

ON THE COVER
Advances in imaging technology have allowed scientists to assess brain size and shape in dinosaurs. Such work has provided fascinating insights into dinosaur intelligence and sensory perception. Researchers are finally beginning to piece together how creatures such as *T. rex* saw, heard and smelled the world around them.

Illustration by Beth Zaiken

Photograph by Spencer Lowell

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Hey. The future is here. We need to get serious.
—Earth
Our planet is talking to us.
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Reshaping our relationship with our world

Dinosaur Consciousness

A **1974 ESSAY CALLED** "What Is It Like to Be a Bat?," which is still taught in cognitive science and philosophy courses, argues that we can never completely understand another organism's consciousness. That may well be, but we're getting closer, and not just for bats. New research combining neuroscience with advanced fossil scanning is revealing the size, shape and specializations of dinosaurs' brains, which can tell us a lot about what it was like to be a dinosaur. In this issue's cover story on page 22, evolutionary biologist Amy M. Balanoff and paleontologist Daniel T. Ksepka reconstruct the perceptions and actions of *Tyrannosaurus rex, Triceratops, Stegosaurus,* and other classic characters. I hope you enjoy the lush and dramatic illustration by Beth Zaiken; see our Contributors column for more about her paleo-art career (*page 5*).

We at *Scientific American* have been fascinated for decades by the discovery that dark matter exists and the subsequent search for its true nature. At the beginning, as physicists Tracy R. Slatyer and Tim M. P. Tait recall on page 30, scientists came up with quite a few great hypotheses, some of which linked dark matter to other puzzles in physics. But now most of the easy answers have been eliminated, as well as many of the not-easy ones. Physicists are expanding the search, and to get a sense of the search space, please delve into the graphic by Tait and senior graphics editor Jen Christiansen on pages 34 and 35. As the authors write, "the scope of the problem is both intimidating and exhilarating."

A long-awaited class of pain relievers could become available soon. One in five adults in the U.S. suffers from chronic pain, and many more people endure temporary, acute pain. Over-the-counter medications can't provide enough relief, and opioids have dangerous side effects. The new drugs, one of which has made it through several stages of clinical trials, block sodium channels in nerves, dampening pain signals before they reach the brain. On page 56, health writer Marla Broadfoot discusses this approach and what it could mean for people in pain.

Today new pain medications and other drugs are tested in animals before they go to human trials. But laboratory models that are more efficient and accurate are being designed to replace at least some rats, monkeys, rabbits, and other guinea pigs. As author Rachel Nuwer explains on page 50, organ-chip technology mimics human cells and tissues; organoids made from a patient's stem cells can show signs of their pathology in a dish; and engineered organs can make it easier for scientists to study rare diseases.

Last year was the hottest year on record, according to the National Oceanic and Atmospheric Administration's 175-year climate history. The average temperature for 2023 was 0.15 degree Celsius hotter than the second-hottest year, 2016, and that margin is itself a record. We have to do something; we have to do a lot of things. Direct air capture would suck carbon dioxide out of the atmosphere, and it's getting plenty of private and public investment. On page 38, journalist Alec Luhn shows how it works, how it could scale up, why it seems promising, and why we should be wary of some of the claims that it will fix climate change.

Einstein's general theory of relativity explains almost everything there is to know about gravity. But it doesn't explain the quantum nature of spacetime, and physicists have been trying for decades to understand quantum gravity. Now a proposed series of lab experiments could finally point us in the right direction, as philosopher Nick Huggett and physicist Carlo Rovelli spell out on page 64, with illuminating graphics, again from our very own great Jen Christiansen. ⬣

Laura Helmuth
is editor in chief
of *Scientific American.*

VERONICA FALCONIERI HAYS

A NEW TYPE OF PAIN PILL, *PAGE 56*

As a medical illustrator, Veronica Falconieri Hays specializes in both the very complicated and the very small. “Molecular biology is my jam,” she says. Ever since studying biology in college, she has loved to peer through powerful microscopes at the molecules and structures that underpin life. “It’s easy to get lost in” these complex worlds, she says. “You just kind of want to keep looking.”

For every project, Hays learns about a new area of science and tries to wrangle that information into a visual representation that will “bring [you] along to learn what I just learned.” In this month’s feature on new pain medications, written by science journalist Marla Broadfoot, Hays illustrated how ion channels allow nerves to fire—and how sodium channel blockers can target them to stop pain at its source.

When Hays worked for the National Cancer Institute in a cell biology lab from 2014 to 2018, scientists were still trying to understand the structure of these ion channels. So she was particularly interested to learn how new drugs are able to target them. “I’m really, really hopeful that these [new medications] are going to help a lot of people who deal with pain in their everyday life,” Hays says.

ALEC LUHN

OUT OF THIN AIR, *PAGE 38*

For nearly a decade Alec Luhn lived and worked in Russia as a news correspondent. He traveled all over the country, reporting on everything from politics to sports to science. One of his first climate stories was on how thawing permafrost is destroying Arctic cities. Later, he wrote about a town taken over by polar bears and about reindeer herders displaced by the oil industry. His time in Russia made it clear to him that climate change was “the big story of our era,” says Luhn, who is now a freelance climate journalist based in England.

For his feature story in this issue, Luhn traveled to California, Texas and Louisiana to visit the sites of current and future direct-air-capture (DAC) plants. This technology promises to suck carbon dioxide from the air, leaving it ready to be sequestered in the ground, but it is costly. Its use is also loaded with important ethical questions, which makes the tech “extremely contentious,” Luhn says. “Is DAC going to save the world by helping us compensate for those last few billion tons of CO_2, or is it just going to perpetuate the fossil-fuel industry that we’re all so heavily reliant on today?”

BETH ZAIKEN

WHAT WAS IT LIKE TO BE A DINOSAUR? *PAGE 22*

Since childhood, Beth Zaiken (*above*) has been enamored by old-school natural history museum exhibits—the ones that use visual tricks to make sculptures and murals behind a glass panel feel like expansive, immersive worlds. “It’s a totally magical illusion,” she says. “It’s like the painting coming alive.” Today Zaiken designs similar murals for museum exhibits, often featuring dinosaurs, mammoths, or other prehistoric fauna. For this month’s cover story, written by evolutionary biologist Amy M. Balanoff and paleontologist Daniel T. Ksepka on what it was like being a dinosaur, she brought the world of a *T. rex* and a *Triceratops* to life.

Zaiken enjoys the challenge of illustrating bygone eras: you have to “imagine Earth in different time periods and transport yourself there.” She lives in Minnesota on a back channel of the Mississippi River and describes herself as a “totally aquatic creature”—one who loves fishing, canoeing and kayaking. The river is home to an abundance of catfish, and she also keeps these native freshwater fish as pets in her 125-gallon aquarium. And she has four dogs and two snakes. “If you give me half a chance, I will fall in love with anything that moves,” Zaiken says.

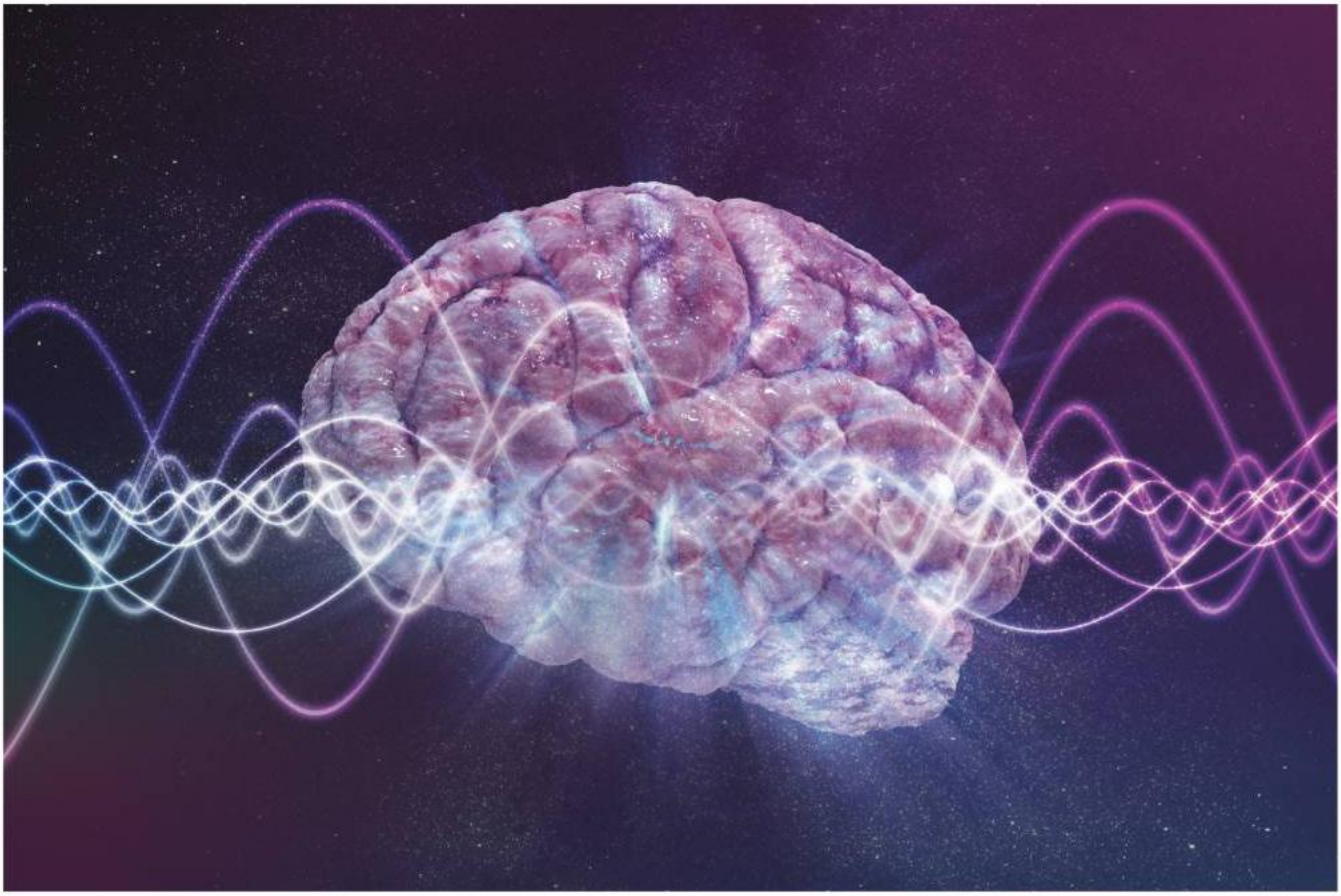
LYDIA DENWORTH

IMPROVING WITH AGE, *PAGE 76*

In high school and college, Lydia Denworth was more of a history and English person—“I took the minimum amount of science classes possible,” she says. Yet in her career as a journalist, she often found herself covering health-related topics. Her first book, published in 2009, followed the scientists who uncovered the toxic effects of lead. “I was really proud of it,” she says. From there Denworth began to delve more into science reporting, often with a focus on neuroscience. “Science felt important. It felt like stories worth telling.” As it turned out, her lack of prior knowledge was an asset that allowed her to ask better questions and explore better explanations.

Now a contributing editor at *Scientific American,* Denworth splits her time between Brooklyn and her family’s farm in central New York State. In her Science of Health column, she writes about new or interesting science that answers questions readers may have about their own health. In this issue, she dispels the pervasive myth that aging always comes with cognitive decline. “There’s just this real cultural stereotype that everybody declines cognitively as they age,” Denworth says. But in reality, “if you have a healthy brain, many people don’t decline almost at all.”

Tim Quady/Blue Rhino Studio



vchal/Getty Images

WHEN NATURE GIVES UP HER SECRETS

Kavli Prize laureates reflect on the moments that led to their lauded discoveries

Science is by nature an iterative process. For every question a scientist might answer, more questions arise. The results of these investigations guide us, step by inquisitive step, to a deeper awareness of our universe.

But some lines of inquiry do more. They provide a path toward unraveling the most profound mysteries we can imagine: the emergence of consciousness, the search for life on Earth-like planets, and the creation of programmable matter.

Every two years, The Kavli Prize is awarded to scientists whose work has transformed the fields of neuroscience, nanoscience and astrophysics. We asked three of this year's prize winners about those eureka moments, when nature reveals a tightly held secret. Their tales highlight their persistence and boldness in venturing into uncharted territory, and those rare flashes of insight when answers are glimpsed that forever alter our understanding of the world.

Co-recipient of the 2024 Kavli Prize in Astrophysics:

Sara Seager, Massachusetts Institute of Technology

Sara Seager shared The Kavli Prize in Astrophysics with David Charbonneau for finding and characterizing exoplanets—those that orbit stars other than our Sun—and their atmospheres. Fresh out of graduate school at Harvard, where she modeled the atmospheres of giant "hot Jupiter" exoplanets, Seager realized that by observing Earth-like exoplanets that passed in front of a star, or "transits," astronomers could reveal chemicals in the atmosphere that were potential signs of life.

Illustrations by Paddy Mills

I have this ability to focus with intense persistence. I credit my autism with that. When I was finishing my thesis, I became obsessed with transiting planets. Something deep inside me told me transits were going to be what moved the field forward.

I started working on this idea that when a planet moves in front of its star, the starlight will filter through the planet's atmosphere—and that the spectral features of the atmosphere's gases would then be imprinted on the starlight. The gist of it is that we can look for the wavelength where the transiting planet appears the tiniest bit bigger—because its atmosphere is strongly absorbing and so it blocks out a little more of the starlight. We can then map out which atoms or molecules are responsible.

I suggested looking for sodium, the gas found in streetlights. At the temperatures of these hot Jupiters, sodium absorbs very strongly at visible wavelengths. So, like a skunk spray, even tiny amounts produce a huge signal.

When I found out that Dave Charbonneau had discovered the first transiting planet, I dropped everything so I could get my paper out the door. My theory about using transit transmission to study exoplanet atmospheres was no longer a random idea for the future—it was an idea for now.

series of therapeutics, some of which have shown the ability to cure forms of cancer.

My dream is that at the end of the day, we will have developed every building block you could possibly need to make a material with any property—for example, the ability to bend light and act as a cloaking material. We love targets like that because it really challenges us to think.

Co-recipient of the 2024 Kavli Prize in Nanoscience:

Chad Mirkin, Northwestern University

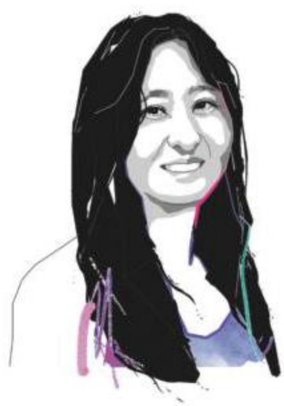
Chad Mirkin shared The Kavli Prize in Nanoscience with Robert Langer and Paul Alivisatos for engineering nanomaterials with biological function to study, diagnose and treat disease. Mirkin designed a novel particle he dubbed a spherical nucleic acid: a gold ball a tenth the size of a typical virus, covered with a dense array of DNA or RNA chains designed to bond with target genetic sequences. Then came the Friday afternoon experiment.

On a Friday afternoon, you should try something impossible, something you might not think will work—just because you're curious. If it doesn't work, go have a beer and talk about how silly that experiment was. If it does work, come to my office for a high five. If we hadn't done that experiment, we never would have discovered that spherical nucleic acids are actively and rapidly taken up by cells. That was an aha! moment.

Once you can move large amounts of nucleic acids into cells, you can begin to ask how to use this tool to understand how cells work, to knock down gene expression, or to differentiate abnormal cells from healthy ones. That set us down the path of developing technologies that could change the field of medicine, including a

Co-recipient of the 2024 Kavli Prize in Neuroscience:

Doris Tsao, University of California, Berkeley



Doris Tsao shared The Kavli Prize in Neuroscience with Nancy Kanwisher and Winrich Freiwald for their discovery of the highly specialized brain region used to recognize and identify faces. Tsao used functional magnetic resonance imaging (fMRI) and single-neuron recording techniques on macaques to locate and listen to individual neurons—and she was amazed to find that she could crack the code the cells were using to represent faces.

I figured that showing monkeys pictures of faces and other objects would be maybe a two-hour experiment, and if it didn't work out, it would just be a lark. We showed a monkey pictures of faces and other objects: vegetables and fruits, hands and bodies, technological objects, and just scrambled patterns. And there was one brain region that would light up on fMRI scans only for faces.

Winrich Freiwald and I did the first recording from a face patch. We stuck our electrode into this patch of brain tissue, amplified the electrical signals, and sent them through a speaker, so we could hear the cell firing. The first cell we were recording responded every time we showed the monkey a face. The next cell was also face selective. It wasn't until maybe the fifth or sixth cell we realized that, whoa, every cell in this area is selective for faces. I was on a cloud.

Years later my postdoc Steven Chang insisted on going after this big problem. We showed a monkey 2,000 faces while recording from individual cells. We found that we could reconstruct each face that the monkey was seeing based on the activity of just 205 face cells.

Of course, there's so much left to discover. Understanding how the brain represents space and objects in space is such a beautiful and mysterious problem.

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

THE KAVLI PRIZE

April 2024

CONSCIOUS FEELINGS

In “A Truly Intelligent Machine,” George Musser outlines future possibilities for the use of artificial intelligence in several fields of study and wrestles with the concept of consciousness.

The primary means of learning in the brains of complex organisms include the experience of pain or pleasure in response to a stimulus. It is this means of learning that AI lacks. If I kick a machine with AI, it will not kick me back unless it is programmed and constructed to do so. (I hope such a machine is never thus programmed.) Even if it could be programmed to fight back, it would never encompass the mass of emotions that millions of years of evolution have shaped in response to situations and conditions that can often change. Our slow synaptic connections cannot compete in speed with computers, but neither can computers be programmed, as yet, with the emotions by which we most often learn about the world.

Because artificial intelligence lacks emotional responses, it cannot be presumed to have consciousness. Absent an emotional component, the goal of creating truly intelligent and self-aware machines is quite a distance away, and I believe that distance may be infinite.

BARRY MALETZKY *PORTLAND, ORE.*

IN-PERSON INNOVATION

In “Facing Facts” [Advances], Simon Makin reports on social scientist Lingfei Wu’s research about how scientists innovate more when they work together in person.

I read the article with interest. In the business world, this effect has been known for a long time. In my experience, teams of any kind working together in person, from sales to basic research, all benefit from collaboration, collegiality and cross-pollination. It is good to have a scientific affirmation of this practice.

JOHN M. BLOCHER *SUGAR LAND, TEX.*

DEGREES OF SEPARATION

“A Nomadic Math Eccentric,” by Jack Murtagh [Math], mentioned the “Erdős number,” a measure of “authorship distance” from mathematician Paul Erdős. That reminded me of something similar that I heard about in chess circles in the 1970s and 1980s: the Fischer number, named after the late mercurial chess genius Bobby Fischer. A Fischer number of one meant that you had played against him. My Fischer number was two.

PETER SMITH
WATTON AT STONE, ENGLAND

EDITOR’S NOTE: *In his 2011 book* The Joys of Chess, *mathematician Christian Hesse proposed a Fischer number based on wins: anyone who defeated Fischer in a game of chess would have a Fischer number of one, anyone who beat someone in that category would have a number of two, and so on.*

EXOPLANET TRAVEL RESTRICTIONS

In “Observations from a Government UFO Hunter” [Forum], Sean M. Kirkpatrick describes the frustration of trying to convince uninformed believers in alien visitors that there is no evidence they exist. Another way to look at this question is: How would they get here?

Of the more than 5,000 exoplanets so far discovered, none has been found to be conducive to the development of intelligent life. So planets with such life are certainly not nearby.

Interstellar travel is impossible for humans because of the speed limit dictated by Einstein’s special theory of relativity, the distances involved and the bounds of life expectancy. Such restrictions would apply to aliens on exoplanets. There is no way for them to get here.

TERRENCE DUNN *VANCOUVER, WASH.*

ANTI-LGBTQ BULLYING

I was glad that you published “Families under Attack,” by Marla Broadfoot. I am transgender and have been the target of bullying many times. There has been a backlash against the LGBTQ movement since Donald Trump was president. I would like to see a follow-up article about why people bully those who are different and what can be done about it.

STELLA ARNOLD *VIA E-MAIL*

SAFE NOISE LEVEL?

“A Healthy Dose of Quiet,” by Joanne Silberner [May], notes the idea that we are prehistorically predisposed to associate noise with danger. It occurs to me that there are noises, such as the chirping of crickets and croaking of frogs, that many people find appealing, soothing or comforting. Admittedly, the noise level generated by these creatures is generally low. And these animals are sensitive to disturbances from approaching creatures: frogs and crickets typically clam up when they detect a potential threat. I speculate that we may find these noises comforting because they indicate that there is no threat in the area.

KARL STEINKE *VIA E-MAIL*

HACKING HUMANS

“Quantum-Proof Secrets,” by Kelsey Houston-Edwards [February], describes how researchers are racing to prepare for

“Absent an emotional component, the goal of creating truly intelligent and self-aware machines is quite a distance away.” BARRY MALETZKY *PORTLAND, ORE.*

a time when a quantum computer will be able to break an essential form of cryptography. It is helpful to think like a criminal when considering future data-security risks.

Social engineering exploits account for most attempted break-ins today. Attacking encryption systems is much more difficult for criminals. Cleverly tricking a credulous employee (or a future artificial-intelligence agent), the same old "con job" used for centuries, will remain the preferred way to commit cybercrimes regardless of future encryption efficacy.

TOBY JESSUP *SEATTLE*

RODENT HEROICS

"Mine Spotting," by Lori Youmshajekian [Advances, December 2023], noted that trained dogs are sometimes used for finding and clearing mines. African giant pouched rats have been successful in clearing mines in Cambodia and certainly warranted mention as well.

ELIZABETH COLEMAN *VIA E-MAIL*

SECURITY DOG

"AI Chatbots Could Weaken National Security," by Remaya M. Campbell [Forum, December 2023], discusses how companion apps pose a risk for users with access to sensitive information.

As a man in his 70s living alone, I never considered a chatbot companion. After reading Campbell's article, I think I'll get a dog. Dogs are loyal and would never reveal a confidence, no matter how many treats they were offered.

MICHAEL SCHEINBERG *AUSTIN, TEX.*

ERRATA

In "How Many Routes?" by Heinrich Hemme [Advances, July/August], the puzzle incorrectly included connections between C and I and between I and M. The error did not impact the solution. The corrected illustration can be seen at www.scientificamerican.com/article/help-a-traveling-salesman-find-every-route-in-this-math-puzzle

"Magnetism vs. Gravity," by Riis Williams [Advances, July/August], should have described interstellar dust across 500 light-years of the galaxy's center, not dust 500 light-years from Earth.

ADVANCES

ANIMAL BEHAVIOR

Long-Distance Contacts

Elephants call one another by name across the savanna

HUMANS HAVE A LONG HISTORY of inventing names for elephants. There is Disney's Dumbo, of course, and Jumbo (a 19th-century circus attraction) and the famed painting elephant Ruby from the Phoenix Zoo. But new research suggests wild African elephants may invent names, too—and use them to call and greet one another on the savanna.

Most animals are born with a fixed set of sounds for communication. A few, such as songbirds, can imitate other sounds they hear around them. Certain species of dolphins and parrots may learn to mimic human words for objects in their environment (like the proverbial Polly who wants a cracker). Much rarer, however, is the ability to attach vocal labels—something akin to names—to fellow members of the flock or pod. Bottlenose dolphins and orange-fronted parakeets are thought to address peers with specific calls, to which a unique receiver tends to react. But in these cases, the calls consist of one animal simply imitating the features of another's habitual or trademark sound. (It's as if someone went around constantly repeating their own name, like "Mark," and you mimicked it back at them.) A dolphin may copy another dolphin's "signature whistle" to attract its attention, and the second animal will respond by repeating that very same whistle.

Now a study in *Nature Ecology and Evolution* reveals that African elephants engage in a type of communication previously unknown in nonhuman animals. Researchers used machine learning to analyze 469 contact, greeting and caregiving rumbles made by wild female savanna elephants in Kenya and discovered that the animals use specific vocal labels to identify one another. Instead of merely imitating an individual's signature call to signal a particular elephant's identity, they come up with an original sound.

"It might seem obvious to me and other elephant researchers that these calls are very specific because you see that a certain individual will respond, but no one has [previously] shown it," says Caitlin O'Connell-Rodwell, an elephant behavioral ecologist at Harvard Medical School, who was not part of the new study.

People typically associate elephants with loud trumpeting, but the most common elephant sound is actually a low-frequency rumble. Some rumbles are so deep that humans cannot detect them—we hear only down to about 20 hertz, and these sounds reach as low as 5 hz. Elephants, however, possess unique ear anatomy designed to pick up such rumbles from as far away as 1.5 miles. This range is important because female savanna elephants live in an elaborate "fission-fusion" society: their extended family units split up and regroup on a regular basis as they follow food resources and avoid predators.

Study co-author Joyce Poole, a co-founder of the charity ElephantVoices, has been studying elephants for almost five decades. She long suspected that these cognitively advanced animals, which show empathy, mourn their dead and may imitate human speech, address one another from afar with something resembling names. She says she has often observed an elephant calling out and only one responding; the others "would just keep on feeding as if they hadn't even heard her," Poole says. "I did wonder, are they being just rude by not answering, or is it because she's actually addressing somebody specific?"

Machine learning helped Poole and her colleagues locate vocal labels among the hundreds of previously recorded female elephant calls. To discern which specific elephants were addressing each other, Poole went back to her old field notes,

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Female savanna elephants call out to their relations at a distance in low, distinctive rumbles.

Byrdyak/Getty Images

looking for interactions such as "so-and-so was separate from so-and-so and was calling so-and-so." The researchers ultimately identified 101 callers and 117 receivers. Next they measured acoustic features of the calls to assess whether they contained individual labels. The resulting model was able to predict the specific receiver of a call with a success rate far better than chance. The vocalizations weren't simply dolphin-like imitation, either; Poole and her colleagues found no statistical evidence of the animals copying one another.

The researchers then verified their findings in the field. They approached 17 wild elephants and played calls addressed to each of them through a speaker. Although the elephants rarely reacted to the "names" of other animals, they quickly responded to their own. "It's a very sharp response," Poole says. "The head jerks up, the ears spread out, the mouth opens wide."

Study lead author Michael Pardo, a behavioral ecologist now at Cornell University, notes that the researchers couldn't pinpoint which part of a call was labeling an individual and that the data were inconclusive on whether multiple elephants use the same name for an individual. It's possible that the recordings simply lack sufficient examples or that different elephants use slightly different versions of the same name. To parse the calls, the researchers may need to collect many more samples of elephant rumbles—a challenging task that would entail spending many hours in close proximity to the studied group. "Collecting this type of data is really intense," says study senior author and Colorado State University biologist George Wittemyer.

Although humans are still just scratching the surface of elephant communication, Wittemyer suggests the existence of individual vocal labels in these calls indicates a capacity for abstract thinking. What's more, he says, studying such labels could add to our understanding of how human language might have evolved. In complex societies where members often lose sight of one another—such as those of elephants or our hominin ancestors—the need to identify others and attract their attention might have driven cognitive abilities and language development.

"If you can name things without relying on imitation, then, at least in theory, it is possible for you to talk about a wider range of subjects because you could potentially come up with names for objects and ideas that don't make any imitable sound," Pardo says.

As O'Connell-Rodwell puts it, "Modifying a vocalization tailored to a specific individual does get you into a conversation. And that's what I would say is a first step."

—Marta Zaraska

COGNITION

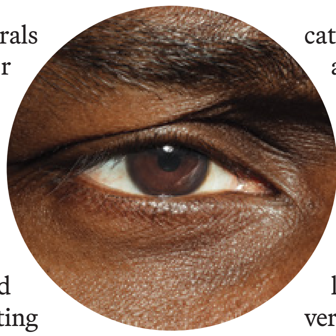
Eye Opener

Pupil dilation is linked to better working memory

FROM A SCIENTIFIC PERSPECTIVE, it may sound a bit too fanciful to call our eyes "windows to the soul." But research suggests that looking into them can, quite literally, offer a peep into a person's basic cognition.

The 10th-century Persian physician Al-Razi (also known as Rhazes) is often credited with connecting pupil size and light exposure. In the 20th century neuroscientists began to investigate pupils' connection to deep-brain processes. They found that pupil size also fluctuates with attention, arousal and anger—and may even be linked to intelligence. Now a study in *Attention, Perception, & Psychophysics* suggests that working memory (the executive function that lets us process, remember and use information) correlates with pupil size, too.

Researchers placed study participants in a light-controlled environment and used a specialized eye-tracking tool to measure pupils during a common test for assessing working memory. Participants viewed a sequence of numerals that flashed on a screen for 2.5 seconds each and then had to determine whether the current digit matched the one they had seen two digits back.



Participants whose pupils dilated more performed better on the task—suggesting pupil size does have a connection with working memory. "The same part of the brain that controls this dilation when something stressful triggers our body to become aroused also controls arousal when we are really focused on a task or doing something cognitively effortful, leading to an increase in pupil diameter," says study co-author Lauren D. Garner, a psychologist at the University of Texas at Arlington.

"Our research specifically focused on individual differences," Garner continues. "We're interested in how people who are more consistent in devoting attention toward a task—and more intensely devote attention toward a task—perform better." This idea is called the intensity-consistency framework.

People who were more successful at the task devoted more intense attention (indicated by increased pupil diameter) more consistently (indicated by less variation in pupil size) than people who performed worse, Garner says. High performers' pupils also dilated more when they looked at numeral matches versus nonmatches.

Tracking links between an individual's cognitive mechanisms and pupil size could be an extremely useful method of analysis. "It's a noninvasive channel of measuring brain state," says neuroscientist Andreas Tolias of Stanford University. "Finding these correlations with performance is yet another indication that pupil measurement is very important."

Garner and study co-author Matthew K. Robison, also a psychologist at UT Arlington, hope that future research can examine how specific physiological brain activity drives pupil size changes. "What would be really cool is to do simultaneous eye tracking and functional neuroimaging," Robison says. "Because then we can really start to look at the temporal dynamics and activity of deep-brain regions."

—Kate Graham-Shaw

master1305/Getty Images

Phantom Costs Why “too good to be true” scares people off

PSYCHOLOGY If a stranger offered you a free cookie, you might well eat it. But what if they offered to *also* give you $2? You might politely decline and walk away thinking, “Something smells fishy.”

In a study published in *Personality and Social Psychology Bulletin*, researchers found that people tend to turn down offers of “free money,” as well as unusually high salaries or suspiciously cheap services, because they seem “too good to be true.” The research bridges economics and psychology to explain why financial incentives backfire.

In the initial experiment, nearly 40 percent of participants ate a cookie offered freely—compared with about 20 percent of those offered $2 as well. “People typically imagine things like someone did something disgusting to the cookie,” says study lead author Andrew J. Vonasch, a psychological scientist at the University of Canterbury in New Zealand.

Nine further experiments, involving more than 4,000 participants, used online questionnaires to present other scenarios. These included being offered money to accept a ride home, outrageously high construction-job wages and surprisingly cheap flights. In each case, past a certain threshold, higher potential monetary gain reduced participants’ likelihood of accepting the offer.

Vonasch says the study illustrates that contrary to the “standard economic model,” which supposes humans always seek to maximize gains, transactions need to also be understood as social interactions between people trying to understand each other’s minds.

If someone seems to violate accepted norms, such as self-interest, without any explanation, we assume they have hidden motives and infer there will be “phantom costs”: imagined consequences that reduce what Vonasch calls an offer’s “psychological value.”

Factors beyond the present moment may come into play. “Understanding that others’ perceived overgenerosity may put us in their debt could also help explain people’s reluctance,” says Rachel McCloy, a psychologist studying decision-making at England’s University of Reading. “The old maxim ‘there’s no such thing as a free lunch’ is clearly alive and well.”

Another experiment found that high scorers on measures of distrust inferred more phantom costs. The researchers also showed how to mitigate the effect: simply provide a reason for the deal. The “cheap flights” experiment included a condition where the seats were revealed to be very uncomfortable. “Uncomfortable seats aren’t typically a selling point,” Vonasch says. “But telling people the seats were uncomfortable made them more willing to take them because it was sufficient explanation.”

The scientists are now experimenting with whether phantom costs play into humans’ interactions with robots and artificial intelligence. “If AI is overly generous, will people imagine phantom costs?” Vonasch says. “People tend to anthropomorphize and treat [AI agents] as if they have a mind, when obviously they don’t.”

—Simon Makin

Illustration by Thomas Fuchs

Fracture line on Greenland's ice sheet

GEOLOGY

Frozen Underworld

A new map shows a complex landscape below Greenland's ice

SCIENTISTS HAVE BEEN TRYING for decades to uncover the true geology of Greenland, an island one-third the size of Australia and almost entirely concealed under mile-deep ice sheets. For a recent study in *Geophysical Research Letters*, scientists constructed a new map that suggests geological details and dramatic terrain hidden underneath the ice.

A lot of people think of Greenland's landmass as being "a big, rigid plate that moves all the same," says study co-author William Colgan, a glaciologist at the Geological Survey of Denmark and Greenland. But it may not be uniform—and understanding how individual geological features might shift and twist below the ice can help improve GPS accuracy for scientific studies and mineral exploration. Mapping Greenland's true geology can also help predict ice-sheet stability because young volcanic bedrock transfers more geothermal heat to ice sheets than older rocks do.

Researchers drew today's widely accepted geological map of Greenland in 2009, largely based on exposed rock along the island's coasts. That approach might work for a smaller, narrower landmass—but not in northern Greenland, where the coasts are more than 500 miles apart and could have dramatic geological variation in between. "If you took North America, put an enormous ice sheet on top of it, and were handed the geology of New York, Maryland or California and asked to [determine] the geology of Nebraska, you would have a hard time making an accurate guess," says Pennsylvania State University geoscientist Sridhar Anandakrishnan.

Since 2009 a burst of new satellites, radar systems and seismic stations has prompted steady growth in datasets available for geological mapping, the researchers say. For their new Greenland map, Colgan and his team processed the available data on changes in gravity, magnetism, crust thickness, bedrock terrain, seismic-wave transmission and ice-surface features across the landmass. Experts analyzed each collection of measurements and noted boundaries between areas with significant variation.

The overlap of these boundaries suggests that Greenland's ice conceals three previously unidentified geological regions, or "provinces," each with distinctive characteristics. One, for instance, seems volcanic in origin and relatively young. Another has rough terrain that could come from extensive hills and valleys. The researchers also spotted thousands of ice-surface features that most likely indicate subglacial valleys, many of them hundreds of miles long and running parallel to one another. And they noticed that ice streams flow faster at the boundaries between some geological regions, suggesting the streams erode those regions in distinct ways.

Measurements along some boundary lines were left to the experts' best guesses. But survey data keep coming in, and Colgan is optimistic: next time his team works on this type of map, he hopes to have larger datasets and better artificial-intelligence analytical tools. *—Saugat Bolakhe*

Jason Edwards/Getty Images

TECH

Gaming Gains

Action-packed video games advance word awareness

IN THE VIDEO GAME Space Invaders Extreme 2, a player has to fire weapons to obliterate aliens attacking Earth. These extraterrestrials move fast, raining down from the top of the screen and claiming a player's "life" if they reach the bottom.

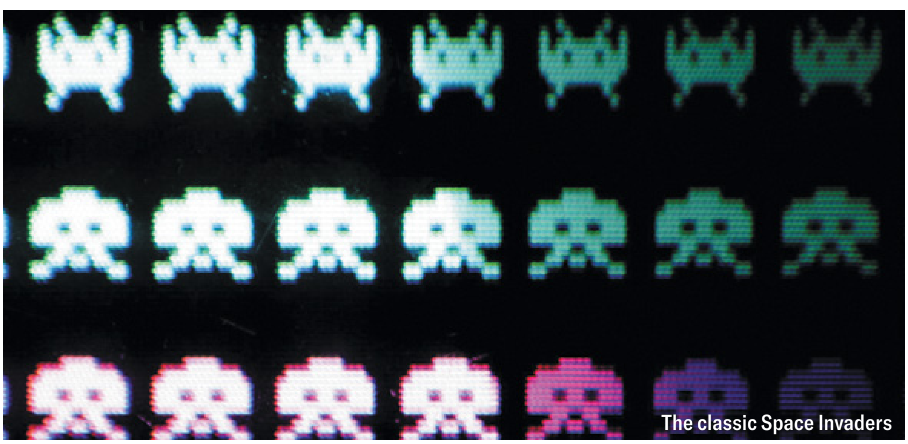
A study in *Nature* suggests such games may help children at risk for developmental dyslexia—a genetic neurological condition that makes processing words difficult—by improving their ability to perceive spoken words and sounds. Destroying digital aliens might seem unrelated to distinguishing between words. But past research has shown that action video games, which a person needs swift cognitive and motor skills to master, activate attention-controlling parts of the brain that process memory.

For the new study, 79 prereading children with family histories of dyslexia took several language tests, including listening for differences in made-up words—a task that can be challenging for dyslexic people. The kids were then split into four groups. One played Space Invaders Extreme 2, a second played a nonaction video game, a third attended speech therapy (the usual treatment for language disorders in Italy, where the study took place), and a fourth received no intervention. Gamers played four times a week for 45 minutes each over a month and a half, and those in speech therapy attended 45-minute sessions twice weekly over about four months.

By the end of the trial more than 80 percent of the Space Invaders players were significantly better at the word-identification task than before, and they showed greater improvements than any of the other three groups. The researchers aren't sure why games boosted this specific task—scores on the other language tests did not improve notably—but they say that this finding could be valuable. "If we can target these small cognitive functions before children are older and lose some brain plasticity, then perhaps we can treat [aspects of dyslexia] before they've fully formed," says study co-author Simone Gori, a neuroscientist at the University of Bergamo in Italy.

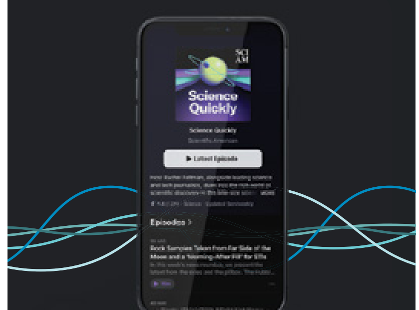
Dyslexia often goes untreated in Italy's overburdened public health and school systems, says Marilu Gorno Tempini, a behavioral neurologist at the University of California, San Francisco, who is from Italy. She says this research offers promise for early-childhood intervention, and she hopes to see larger future studies conducted in other languages as well. The new study is one of the first of what Khizer Khaderi, a Stanford University neuro-ophthalmic surgeon, predicts will be many to demonstrate that video games can help people with learning disorders. "Eyes are an extension of the brain," he says, "so when we play video games, it's directly connected to our cognitive function—and there is so much research potential there."

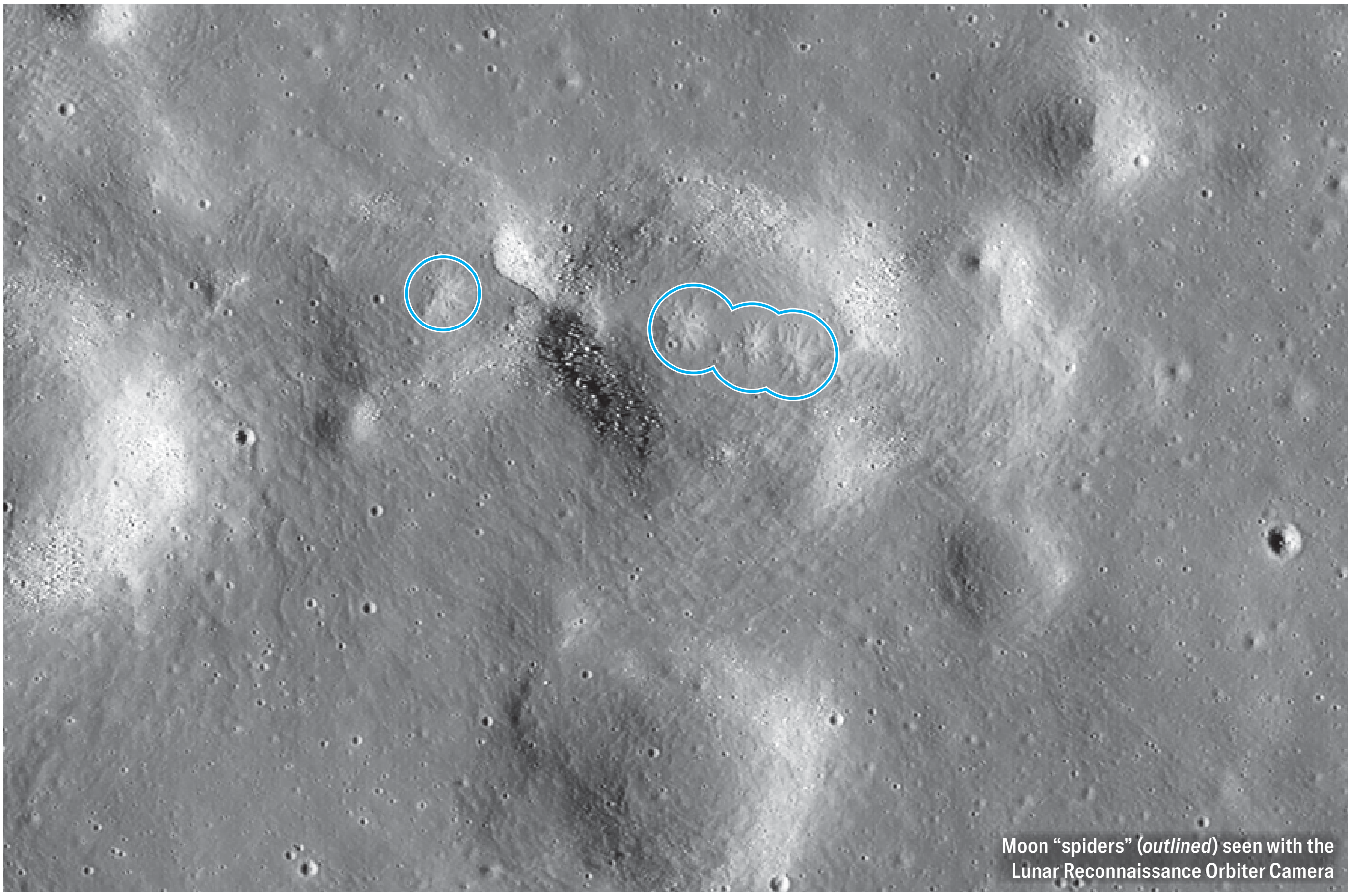
—*Riis Williams*



The classic Space Invaders

Peter Macdiarmid/Getty Images





Moon "spiders" (*outlined*) seen with the Lunar Reconnaissance Orbiter Camera

PLANETARY SCIENCE

Moon Spiders

Features hint at spacious underground moon caves

LAVA PLAINS and volcanic residue on the moon's surface point to the orb's fiery past. What's below, though, remains mostly a mystery. But in a study in the *Planetary Science Journal*, researchers describe an odd surface feature that supports the presence of underground caves termed subsurface voids.

Each so-called spider formation consists of multiple gullies (the spider's "legs"), which seem to have formed when lunar soil flowed into a central indentation about 10 meters wide (the spider's "body"). The researchers spotted the first four spiders hiding almost imperceptibly in a photograph from the powerful cameras on NASA's Lunar Reconnaissance Orbiter (LRO): "The spider legs are almost at the edge of resolution," says the study's lead author, Mikhail A. Kreslavsky, a planetary scientist at the University of California, Santa Cruz.

Once they knew what to look for, the scientists found several more spiders, all in Mare Tranquillitatis—a region with a turbulent volcanic past. Brown University planetary geoscientist and study co-author James W. Head says the relatively low lunar gravity likely allowed big bubbles of gas to form in magma, leaving behind subsurface voids. If these voids' ceilings collapsed because of seismic activity, the authors say, inward-flowing surface material would have created the distinctive spider shape.

In an earlier study, LRO detected a void extending under a large pit in Mare Tranquillitatis, and researchers have speculated that some of the moon's roughly 300 other known pits have spacious caves below.

The study authors suspect many more spiders once existed and were erased. "There are still lots of micrometeorites that hit the moon's surface," says Nicolle Zellner, a planetary scientist and physicist at Albion College in Michigan, who also studies the lunar surface. "The upper meter of material is churned by the bombardment."

LRO project scientist Noah Petro of NASA's Goddard Space Flight Center says the spiders' proximity to other signs of ground disturbances in volcanic deposits called irregular mare patches, and the possibility that spiders might have once appeared near pits, could suggest the voids are larger than thought or that they're connected underground. "Maybe voids are far more extensive than we previously assumed," he adds.

Because today's spiders likely formed within the relatively recent geological past, they serve as a warning for future explorers that, in certain places on the moon, dangerous caverns may still lurk below the brittle surface. —*Theo Nicitopoulos*

ASTRONOMY

Galactic Slime

Slime molds help to map the hidden shape of the cosmos

OVER BILLIONS OF YEARS gravity has pulled the universe's matter into a chaotic netting of filaments, tendrils and voids known as the cosmic web. Galaxies are strewn along these strands like beads on a string, and New Mexico State University astronomer Farhanul Hasan and his colleagues wondered how environments created by the filaments affect galaxies' evolution. "I like to call them galactic ecosystems," he says.

To find out, the researchers needed to accurately map the cosmic web over time. But the mixture of gas, galaxies and dark matter that constitutes the web makes this task challenging, because although the stars in the galaxies are easy to see, the rest is not.

To connect the dots in a computer simulation of the universe, Hasan and his colleagues brought in a special "collaborator": a species of the humble slime mold. These single-celled organisms are experts at exploring the space around them. Their membranes push outward in a synchronized wave in every direction. When they find a food source, nearby membranes relax, allowing subsequent pushes to send more material to that region.

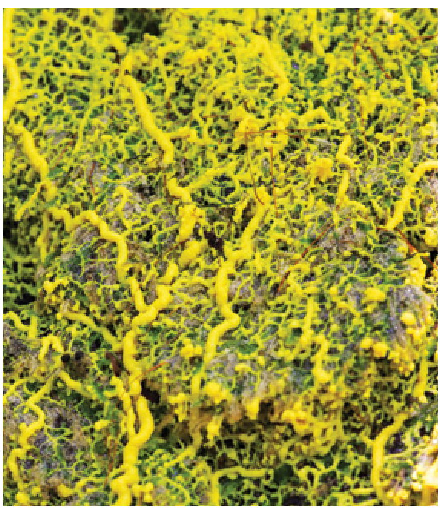
Scientists have used slime molds' exploration prowess to solve mazes and logic puzzles, to re-create transportation systems, and to inspire efficient computer algorithms. "It's a really good mapping algorithm because it's not really biased by the first direction you decide to look in; [it's] capable of exploring everything at once," says New Jersey Institute of Technology slime mold specialist Simon Garnier.

Hasan and his team gave a slime-mold-based algorithm a set of galaxies' positions as "food" and let it map connections across the simulated universe at various time points. The slime-mold map created a cleaner filament structure than any human-designed algorithm they had tried; it was also sensitive to smaller features and traced dark matter more easily. The researchers found that neither the proximity nor the thickness of the universe's filaments seemed to affect the galaxies early on, but as the universe matured, things changed: material pulled into the web eventually disrupted star formation in galaxies that were too close.

A slime mold is "capable of exploring everything at once." —Simon Garnier *New Jersey Institute of Technology*

"The crucial difficulty in using the cosmic web to constrain galaxy formation is in describing it with the accuracy needed to observe its effect," says New York City College of Technology astrophysicist Ari Maller. "The use of the slime-mold algorithm seems to have accomplished that goal."

The study's results, appearing in the *Astrophysical Journal,* are just the beginning. New surveys are stretching observations even further back in time. Conclusions from the simulated universe eventually can be tested against older glimpses of the real cosmic web—and the slime-mold algorithm is poised to map them all. —*Mark Popinchalk*



TommyIX/Getty Images

SCIENCE IN IMAGES

Deep Strength

Why comb jellies withstand crushing depths but melt away on land

IN THE OCEAN'S DEPTHS, seawater's punishing weight would crush most surface-dwelling species to a pulp. So how do ctenophores—squishy, see-through creatures with bodies the consistency of Jell-O—thrive kilometers deep?

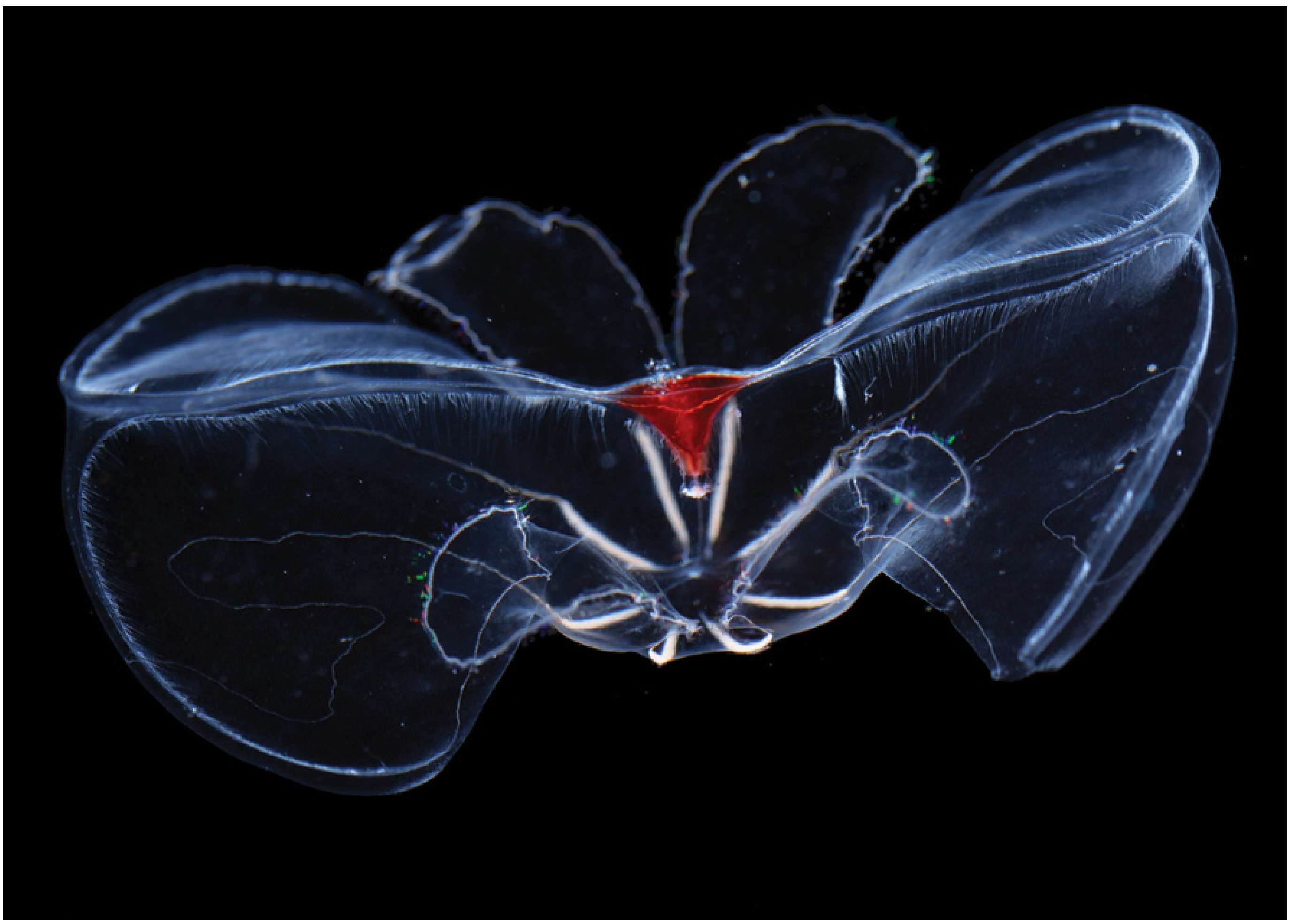
Research published in *Science* explains how deep-sea ctenophores keep it together under extreme pressure and why they "melt" like the Wicked Witch of the West when brought to the surface. "For some deep-sea ctenophores, their cell membranes are literally held together by pressure," explains the study's lead author, Jacob R. Winnikoff, a deep-sea biochemist at Harvard University.

Ctenophores, also called comb jellies, are ghostly-looking bags of goo whose crystalline combs—structures they use like tiny oars to move through water—refract light into rainbows. Despite their ethereal looks, they're voracious predators found slurping up plankton, crustaceans and small fish from pole to pole of our watery globe. And despite their name, they're not closely related to jellyfish.

To suss out what makes deep-water ctenophores so graceful under pressure but oozy at the surface, researchers around the world collected comb jelly species that live at a range of depths. Scuba divers scooped shallow-water ctenophores from the ocean off Hawaii's Big Island and in the Arctic, for instance, and remotely operated vehicles gently vacuumed up those creatures' cousins at depths of up to four kilometers below the waves off the coast of California.

Comparison of the animals' body tissues revealed that the deeper a comb jelly lives, the higher its level of PPE, short for plasmenyl phosphatidylethanolamine—a variety of cone-shaped phospholipid, which is a fatty molecule found in cell membranes.

At high pressures all molecules are slightly "squeezed" out of shape, Winnikoff explains—and because lipids are particularly squishy, cone-shaped lipid molecules warp into cylinders in the ocean's depths. Usually combinations of cone- and cylinder-shaped lipids balance a cell membrane's stability and flexibility. Without enough cones the cylinders lock together like bricks, and the business of the cell breaks down, he says. Proteins, the



Jacob R. Winnikoff/Harvard University

"machines" of the cell, don't have the wiggle room they need to move and operate. Signals can't enter or exit, and the cell is functionally paralyzed.

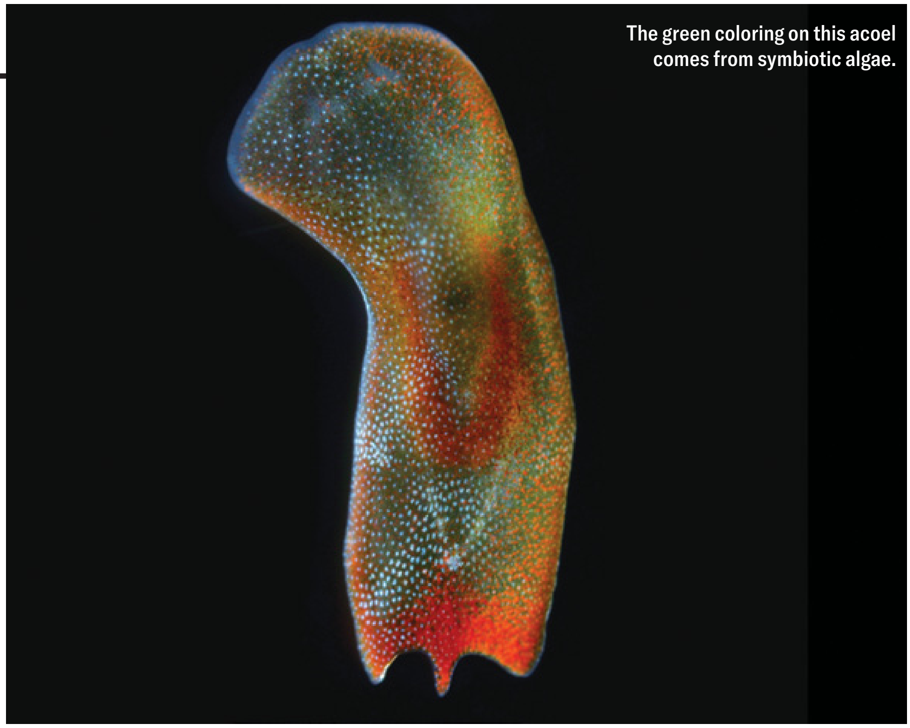
By using a particle accelerator to map out PPE's structure, Winnikoff and his team discovered that the molecule's cone flares more dramatically than that of any other phospholipid ever documented. PPE's shape is exaggerated enough, the researchers found via modeling, to remain a cone even under compression.

But there's a downside: comb jellies adapted to life in the deep need that high pressure to keep their membranes intact. If it's reduced, PPE's conical shape expands; this change causes cell membranes to ripple, crack and ultimately curl up into nanoscopic "macaroni" shapes, the researchers found.

On a whim, the scientists next used genetic engineering to increase PPE levels in *Escherichia coli* bacteria, replacing about a quarter of the bacteria's phospholipids with PPE. They found that although *E. coli*'s growth typically slows under pressure, the new, higher-PPE strain "performed exactly the same" at surface pressure and a simulated depth of five kilometers, Winnikoff says.

The team's findings are "fantastic" and "answer a very, very long-standing question about ctenophores," says Cornelia Jaspers, an ecologist studying these animals at the Technical University of Denmark. Sanna Majaneva, a marine ecologist at the Norwegian aquatic research institute Akvaplan-niva, says it's gratifying to finally know why so many of her specimens have "dissolved," "crumbled" and "shivered" apart before her eyes since she began working with ctenophores more than a decade ago.

This work could aid research on landlubbers, too: PPEs are part of the human nervous system, and their loss is associated with conditions such as Alzheimer's disease. Pinning down the extent of PPE's curve, as done for the first time in this study, and knowing how to manipulate levels of the molecule could suggest new avenues to explore in the search for neurological treatments, says co-author Itay Budin, a biophysicist at the University of California, San Diego. "It's not just relevant to the deep sea," Budin says. *—Elizabeth Anne Brown*



The green coloring on this acoel comes from symbiotic algae.

Eric Röttinger

Helpful Guests Regenerating ocean worms harness live-in algae as they split into three

BIOLOGY At first glance, tiny flatworms called acoels seem pretty simple. Their few internal organs drift freely in their shapeless bodies, which lack even a digestive tract.

Some acoel species host photosynthesizing algae that provide energy in exchange for safe housing, a classic example of symbiosis. And these acoels can do something remarkable: if cut in half, they split into not just two but three new, thriving versions of themselves. First a single new tail grows from the head, and then two Hydra-like heads erupt from the tail before it splits into two more separate organisms. Now a study in *Nature Communications* suggests these worms manipulate their live-in algae's gene activity during this extreme act of regeneration. Scientists find this intriguing because many coral species also depend on symbiotic algae—which today's warming seas are increasingly forcing to abandon their hosts, causing coral bleaching and sometimes the collapse of entire ecosystems.

Study co-author Bo Wang and his colleagues found that when they intentionally injured acoel worms, the algae's photosynthesis became less efficient as the worms began to regenerate. But simultaneously, the algae's photosynthesis genes became more active, potentially compensating for the shortfall. Experimentation suggested that a worm gene called *runt*, when activated to help regeneration, likely made a protein that prompted the algae to switch on these particular genes. "Here the host cells are directly regulating the algal cells, potentially for the benefit of the host system," says Wang, a developmental biologist at Stanford University. "The photosynthetic pathway being controlled by the regenerative program of the host—that was the most surprising thing for us."

"A lot of studies tend to look at symbiosis from the animal side because people are interested in the animals more than the algae," says Yixian Zheng, a developmental biologist at Carnegie Science in Baltimore, who studies algae-harboring corals. "This paper's strength is that they focus on the response of the symbiont, the algae, directly connecting the algae response to the host regeneration."

Learning how hosts control their algal partners could help researchers manipulate the algae within corals and possibly restore interactions that are lost because of stress, Wang says. He's also curious about how the algae that benefit acoels seemingly control their landlords in turn—for instance, how the algae sometimes prompt the usually photophobic worms to spread out like solar panels, exposing the resident algae to the sun. *—Rohini Subrahmanyam*

Michael Svoboda/Getty Images

ANIMAL BEHAVIOR

Puppy Eyes

Domestic dogs' exaggerated faces are hard to read

CENTURIES OF BREEDING to make our canine companions suit human aesthetics have left them less able to communicate through facial expressions than their wolf ancestors were, new research shows.

Dogs with exaggerated physical traits, such as floppy ears and the short, squashed muzzles of pugs and Boston terriers, fared worst at expressing themselves with their faces alone, according to a study in *Scientific Reports.* Long fur and prominent flews (the loose upper lip seen in bulldogs and boxers) also obscured dogs' expressions. In general, the less wolflike a dog's facial features, the weaker its ability to express emotion, says study lead author Elana R. Hobkirk, a canine behavioral ecologist at Durham University in England.

To measure how well a canine face reveals the animal's emotions, Hobkirk logged the subtle facial movements of captive wolves and kenneled rescue dogs while they were interacting with one another or with humans and as they responded to various stimuli; a squeaking sound with no visible toy, for example, elicited curiosity. By looking at recordings of the canines' reactions, Hobkirk identified nine emotions (such as anxiety, curiosity, happiness and surprise) and then tested how well they could be detected based on only facial-movement data, excluding barks and body language.

The researchers found that facial movements revealed domestic dogs' emotions about two thirds of the time. Their model struggled, however, with breeds that look less like wolves, which accounted for nearly all of the incorrect predictions. (Wolves' expressions were accurately interpreted three quarters of the time.) Domestic dogs' features can prevent them from expressing cues with their ears and minimize their ability to bare their teeth. Fear was most often confused for other emotions, especially happiness—a particular concern for people who are less familiar with dogs. If you misinterpret a dog's face when approaching it, "you could get bitten," Hobkirk says.

"We don't yet have comprehensive knowledge about how dogs may use those expressions they produce differently than wolves," says canine researcher Annika Bremhorst of the University of Bern, who hopes to see further research on this topic. The study notes that dogs with impaired facial expression appear to compensate by using communication cues such as barking to convey emotion. *—Lori Youmshajekian*

MATH PUZZLE

One One

What comes next in the pattern?

BY SARAH LEWIN FRASIER

SOME OF THE MOST SATISFYING NUMBER PUZZLES require little mathematical know-how. In fact, cracking the one below calls for thinking that is quite nonmathematical. I don't know where or when I first encountered this sequence—it must have been around middle school. But after researching it more recently, I was unsurprised to find that mathematician John Horton Conway, a lover of recreational mathematics well known for his zero-player Game of Life, wrote a playful paper about the pattern and its variants for the University of Cambridge student journal *Eureka*. This puzzle's combination of seeming impenetrability, generative complexity and a simple solution makes the sequence delightful to solve and to share.

And so, without further ado: What comes next in this pattern?

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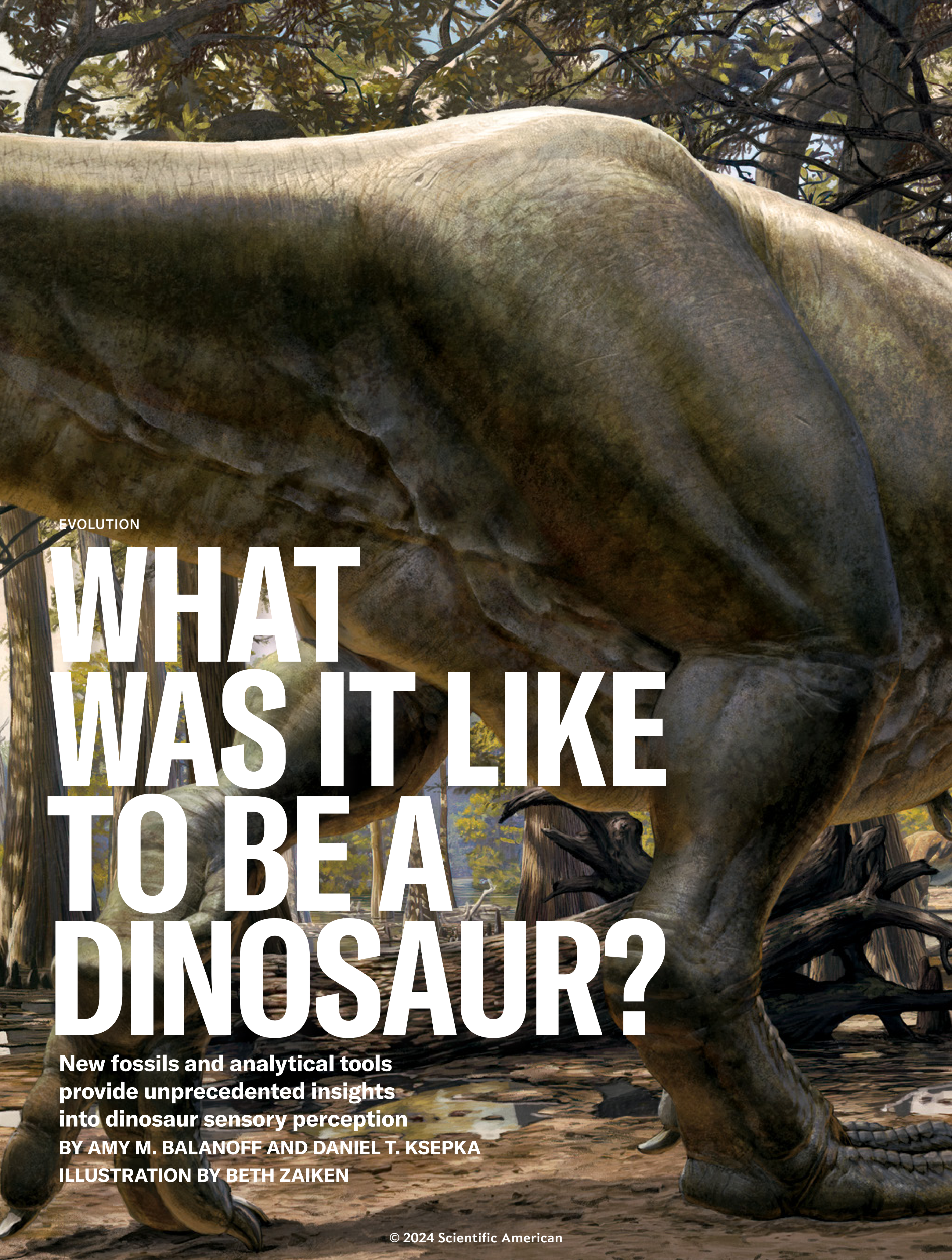
11
21
1211
111221
312211

For the solution, visit www.ScientificAmerican.com/games



EVOLUTION

WHAT WAS IT LIKE TO BE A DINOSAUR?

New fossils and analytical tools provide unprecedented insights into dinosaur sensory perception

BY AMY M. BALANOFF AND DANIEL T. KSEPKA

ILLUSTRATION BY BETH ZAIKEN

A LONE ***TYRANNOSAURUS REX*** **SNIFFS** the humid Cretaceous air, scenting a herd of *Triceratops* grazing beyond the tree line. As the predator scans the floodplain, its vision suddenly snaps into focus. A single *Triceratops* has broken off from the herd and wandered within striking distance. Standing motionless, the *T. rex* formulates a plan of attack, anticipating the precise angle at which it must intersect its target before the *Triceratops* can regain the safety of the herd. The afternoon silence is shattered as the predator crashes though the low branches at the edge of the forest in hot pursuit.

T. rex has hunted *Triceratops* in so many books, games and movies that the encounter has become a cliché. But did a scene like this one ever unfold in real life? Would *T. rex* identify its prey by vision or by smell? Would the *Triceratops* be warned by a loudly cracking branch or remain oblivious because it was unable to locate the source of the sound? Could *T. rex* plan its attack like a cat, or would it lash out indiscriminately like a shark?

Ever since dinosaurs were first described in the early 1800s, paleontologists have debated their intelligence, sensory capabilities and behavioral complexity. Early investigations relied on natural endocasts, which are casts formed when sediment fills the empty space in a skull. These casts replicate the shape of the braincase's contents in life. The conventional wisdom long held that all dinosaurs had tiny brains and therefore unsophisticated behaviors. Perhaps the most amusing example of this view of dinosaur intelligence came from 19th-century paleontologist Othniel Charles Marsh, who hypothesized that the armored dinosaur *Stegosaurus* had a second brain near its rump to supplement the walnut-size brain in its skull. This idea was based on a vaguely braincase-shaped expansion of the spinal canal near the dinosaur's pelvis. The mysterious expansion is now thought to represent a glycogen body—a structure that stores energy-rich glucose and occurs in a similar position in some modern birds.

Present-day paleontologists remain unconvinced that *Stegosaurus* was capable of much higher reasoning. But in recent years scientists' appraisal of the cognitive capacity of some other dinosaurs has improved, particularly that of members of the theropod lineage that gave rise to birds. With the advent of new technologies, such as micro computed tomography (CT) scanning, we can now reconstruct the volume and surface topography of brains without having to depend entirely on rare natural endocasts, greatly expanding the number of species available to study. Advanced imaging is also teaching us how dinosaurs might have used their brains. We now have the tools needed to answer the question of how long-vanished animals perceived the world around them and what really happened when predator met prey in the age of dinosaurs.

WHERE DID *T. REX* FALL on the intelligence spectrum between dim-witted *Stegosaurus* and tool-using ravens? In a high-profile paper published last fall, neuroscientist Suzana Herculano-Houzel of Vanderbilt University suggested that a *T. rex* was about as smart as a baboon—a startling conclusion because primates, with their large brains, are some of the clev-

Amy M. Balanoff is an assistant professor of functional anatomy and evolution at Johns Hopkins University. She studies the evolutionary history of the modern bird brain.

Daniel T. Ksepka is a paleontologist and science curator at the Bruce Museum in Greenwich, Conn. His research focuses on the evolution of birds and reptiles.

erest animals around. Having spent long hours pondering the way brain volume scales with body size and what this relation means for brain function in extinct dinosaurs and birds, we were intrigued to see the headlines about this study. Superficially, the brain of the tyrant lizard king looks fairly puny compared with its body size. Weighing in at less than a pound, the brain of this six-ton dinosaur is diminutive next to the 11-pound brain of the African elephant, which, despite being the largest living terrestrial mammal has a smaller body than *T. rex*.

Herculano-Houzel argued that the relation between brain size and body size is unimportant when it comes to intelligence. What matters, she said, is the raw number of neurons in the telencephalon, a region in the front of the brain that includes not only the olfactory bulbs that process smell but also the cerebrum, where higher cognitive functions such as decision-making occur. Scientists previously had only an imprecise understanding of how many neurons were present in vertebrate brains because in different species they can be more or less densely packed in different parts of the brain.

Herculano-Houzel and Roberto Lent of Federal University of Rio de Janeiro invented a technique for counting neurons called the isotropic fractionator method. It uses special chemicals to dissolve a brain, essentially making brain soup. A fluorescent dye stains the nuclei of neurons so that they glow and are easily visible. Researchers can precisely count the glowing nuclei in a small, homogeneous sample of the soup and then extrapolate the total number of neurons in the living brain. Using this method, Herculano-Houzel and her colleagues calculated that human brains have approximately 100 billion neurons, confirming earlier estimates.

> A *T. rex* with the intelligence of a primate would be terrifying. We think some caveats are in order, however.

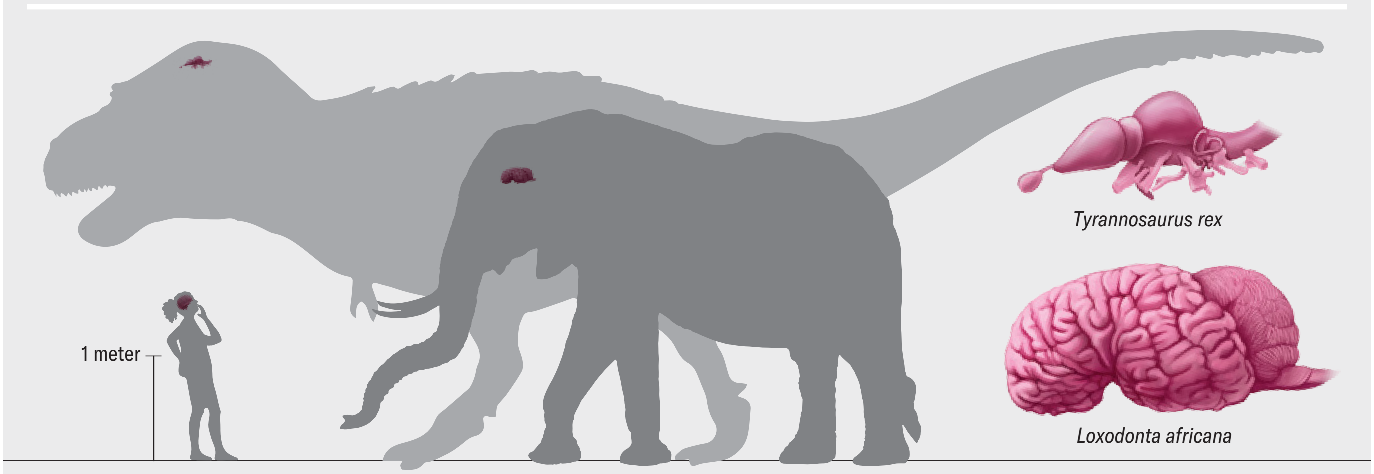
The isotropic fractionator method is clever, but scientists will never have an actual *T. rex* brain to dissolve. Instead Herculano-Houzel relied on the scaling relation between telencephalon size and neuron numbers for living warm- and cold-blooded species, plugging extinct dinosaurs into one of two equations based on their inferred metabolism. This scaling relation varies tremendously among vertebrates. Cold-blooded, or ectothermic, species tend to have less tightly packed neurons than warm-blooded, or endothermic, species.

For example, isotropic fractionator data reveal that a 159-pound Nile crocodile has about 81.5 million neurons, whereas a 73-pound emu has roughly 1.3 billion neurons—almost 16 times as many as the crocodile despite being only half its size. Herculano-Houzel contended that most theropod dinosaurs were probably endothermic and thus near the bird end of the neuron-density continuum. Under this assumption, a *T. rex* telencephalon weighing roughly 12 ounces would contain around three billion neurons, on par with those of many primates.

A *T. rex* with the intelligence of a primate would be terrifying. We think some caveats are in order, how-

How Smart Was *T. rex*?

A recent study concluded that *Tyrannosaurus rex* was as clever as a primate. Could that terrifying claim be true? *T. rex* was larger than an elephant, yet it had a much smaller brain. Researchers typically look at measures of brain size compared with body size to estimate the cognitive capacity of vertebrate animals. By this simple metric, *T. rex* is unlikely to have had primatelike intelligence. In addition, large regions of the brain of *T. rex* were associated with functions such as olfaction rather than higher cognitive functions such as advance planning—more evidence that this dinosaur lacked primatelike smarts.



Graphics by Mesa Schumacher

ever. Besides the reasonable supposition that theropods were endothermic, the estimate of three billion neurons relies on a few other assumptions. One is that the entire braincase was occupied by the brain, which is clearly not true based on the morphology of *T. rex* endocasts. Fossil evidence indicates that in many dinosaurs, structures such as sinuses and blood vessels took up substantial parts of the braincase. Actual brain volume would have been smaller than raw endocranial volume. In fact, studies based on modern crocodilians suggest that the brain of *T. rex* might have occupied as little as 30 percent of the overall endocranial volume.

It's also important to note that different brain regions have different functions. Some are devoted to tasks as basic as the regulation of breathing, whereas others support functions as complex as language. Two species with the same telencephalon size may have vastly different cognitive capacities if the cerebrum dominates the brain size of one and enlarged olfactory bulbs dominate the brain size of the other. For living species, it is possible to determine the boundaries between different brain regions with techniques such as cell staining or magnetic resonance imaging.

Defining these boundaries is much harder for dinosaurs because all we have to work from is the surface topology. One of us (Balanoff) has spent a significant part of her career mapping out bony landmarks that allow for better estimates of the volumes of major brain regions from endocasts. This work has shown that expansion of the cerebrum arose in more specialized theropods such as oviraptorosaurs and dromaeosaurs—lineages that branched off much later than tyrannosaurids. In contrast, earlier-diverging theropods such as *T. rex* had relatively small cerebrums, with a large portion of the overall telencephalon given over to the olfactory bulbs.

Once we account for the volume of nonneural tissues housed in the endocast, it's unlikely that *T. rex* had three billion neurons of any kind in its telencephalon. We agree that *T. rex* was a proficient predator, but we argue that it was probably not capable of the advanced planning or coordinated social hunting seen in primates.

ONE OF THE BEST THINGS about working with fossil endocasts constructed from CT scans is that we can study interior features without damaging the fossils themselves. Virtually chopping up fossil endocasts is a delightful way to spend an afternoon. Exploring the brain slice by slice, a trained paleontologist can use bony landmarks to decipher the boundaries of key brain regions and isolate those regions digitally. As we segment the brain from front to back, the olfactory bulb is the first structure we encounter. Olfactory bulb shape varies dramatically in dinosaurs and their relatives. Alligator olfactory bulbs are about the size of small grapes and are positioned at the end of long stalks leading to the rest of the brain. The olfactory bulbs of most birds are much smaller; in fact, in many species they are barely distinguishable from the rest of the cerebrum.

As the name implies, the olfactory bulb facilitates smell—a sense that relies on tiny molecules called odorants. Inhaled odorants bind to receptors in the nasal tissue, which communicate via neurons to the olfactory bulbs. Amazingly, each receptor makes a single odorant-receptor protein, which is tuned to specific types of odorants. Each of these proteins is coded by a different olfactory receptor gene. Genomic sequencing has revealed that birds have anywhere from 182 to 688 functional olfactory receptor genes.

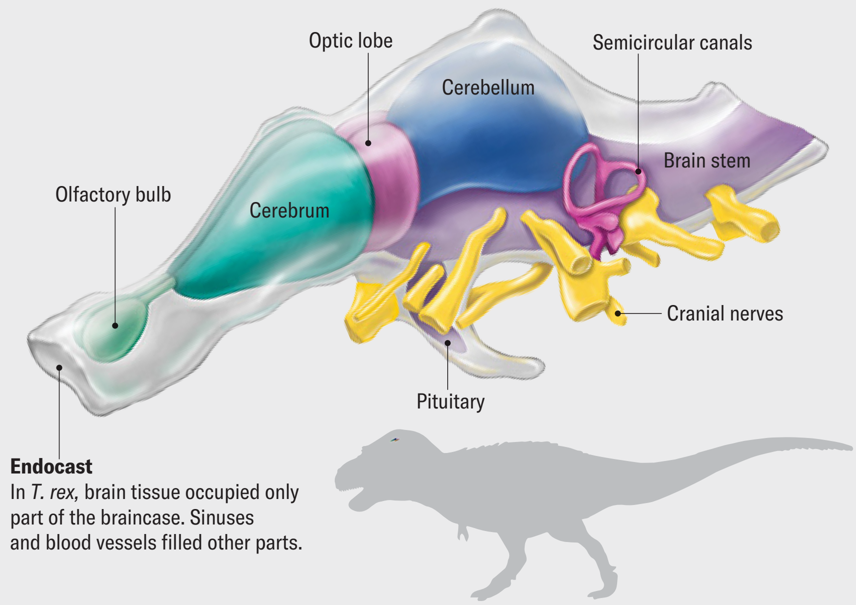
In a recent study, Graham Hughes and John Finarelli of University College Dublin investigated dinosaurs' sense of smell. The number of olfactory receptor genes in dinosaurs cannot be measured directly, but because bulb size correlates to the number of receptors, bulb dimensions can serve as a proxy for how well the animals could detect odors. Hughes and Finarelli found that, in general, dinosaurs had proportionally larger olfactory bulbs than birds. Among theropods, the omnivorous ornithomimosaurs had the smallest olfactory bulbs, and carnivorous species had the largest. *Tyrannosaurus* topped the charts with olfactory bulb dimensions consistent with the presence of more than 600 olfactory receptor genes. This number is on par with domestic cats and higher than in almost all modern birds. Our hypothetical *Triceratops*-stalking *T. rex* really would have been able to sniff the wind and identify both living prey and carcasses to scavenge long before laying eyes on them.

Other work on CT-based endocasts hints at how sharp *T. rex*'s eyes were. By virtually slicing up endocasts and isolating the optic lobes, we have found that the relative sizes of these structures were similar in extinct theropods and living birds. Birds therefore must have inherited their visual acuity from their nonbird ancestors. Birds are known to be highly visual animals—an eagle can spot a rabbit from half a mile away, and a tern in flight can track a fish half an inch long below the surface of water and pick it off from above. This reliance on sight is reflected in the structure of the bird brain. The optic lobes, which process visual information and reside just behind the cerebrum, are some of the brain's most prominent features. It is often true that the larger a region is relative to the rest of the brain, the more important that

T. rex really would have been able to sniff the wind and identify both living prey and carcasses to scavenge long before laying eyes on them.

T. rex Brain Anatomy

Researchers use medical technology such as CT scanning to build digital endocasts of extinct dinosaurs, allowing reconstruction of their sensory capabilities. The endocast of *T. rex* shows it had a brain adapted for a predatory way of life. The expanded olfactory bulbs indicate an excellent sense of smell that would have been useful for locating prey; large optic lobes mean that *T. rex* also was probably capable of identifying and following prey with its eyes.



Sources: "New Insights into the Brain, Braincase, and Ear Region of Tyrannosaurs (Dinosauria, Theropoda), with Implications for Sensory Organization and Behavior," by Lawrence Witmer and Ryan Ridgely, in *The Anatomical Record*, Vol. 292; 2009, and "Gross Anatomical Brain Region Approximation (GABRA): Assessing Brain Size, Structure, and Evolution in Extinct Archosaurs," by Ashley Morhardt, doctoral dissertation, Ohio University, 2016 (*endocast references*)

region is to the animal. This certainly holds for the optic lobes.

We can infer some visual capacities of extinct dinosaurs from their evolutionary relationships. For example, both birds and crocodilians—the closest living relatives of the extinct dinosaurs—have the types of retinal receptors needed to see in color. So dinosaurs most likely had color vision, too. Vision is a complicated sense, however. Accurately reconstructing just how well extinct dinosaurs could see requires us to go beyond these types of inferences.

One factor that makes predatory birds so adept at capturing prey is stereoscopic vision—an enhanced ability to perceive depth. The sensory adaptation that underlies this sophisticated capability is astonishingly straightforward. It simply has to do with the position of the eyeballs. Animals with eyes positioned on the side of the head, such as geckos, lack overlapping visual fields, so they don't see well in three dimensions. Animals with eyes positioned on the front of the head have visual fields that overlap in front of the nose. Within this overlapping space, each eye perceives the same information from a slightly different perspective, producing what is known as binocular vision.

Try fixing your gaze on an object about a foot or so in front of you, then closing one eye and then the other. The object will seem to move because you're seeing the same image in front of your nose but from different angles. The brain integrates these slightly different images to produce visual depth. Animals with laterally positioned eyes judge depth by looking at something with one eye, moving their head and then looking at it with the other eye—not an especially stealthy technique. For a predator, binocular vision is particularly useful because it allows the animal to identify and zero in on prey without potentially disclosing its location by moving its head.

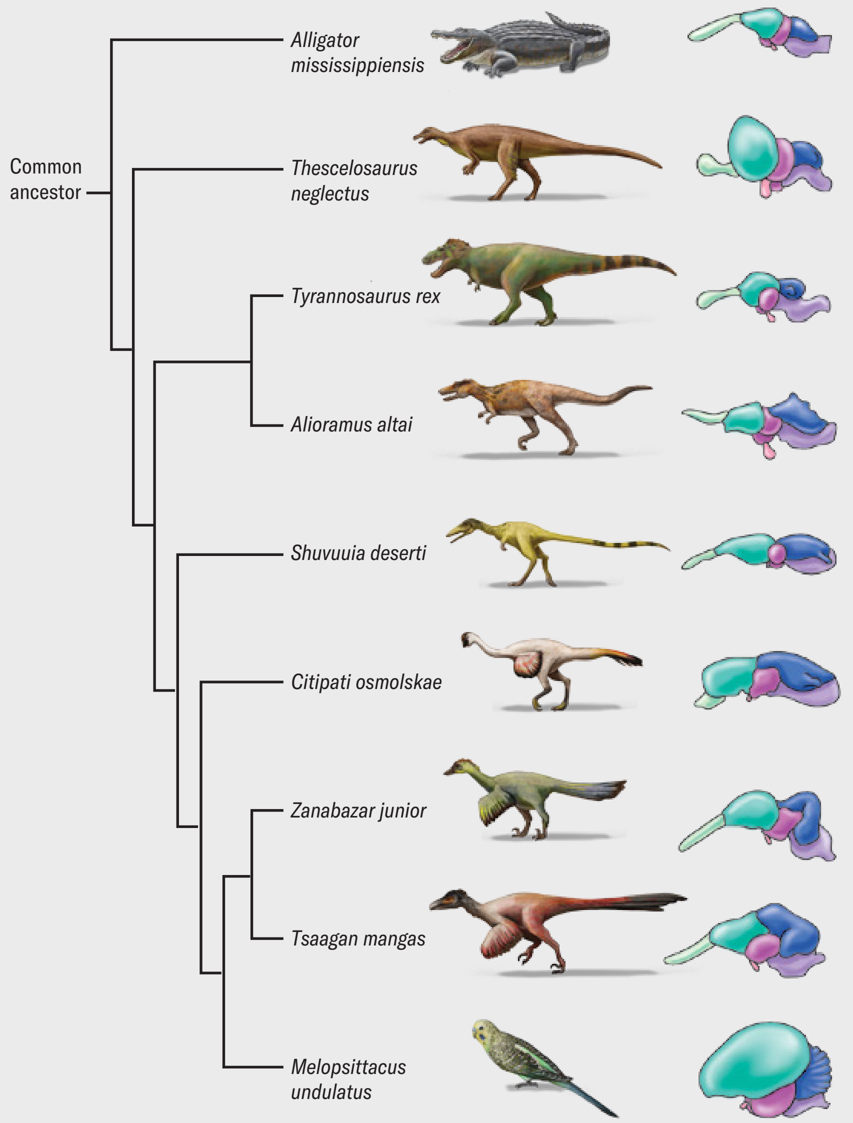
To determine whether extinct animals had stereoscopic vision, we must consider the position of their orbits, which are the spaces in the skull that house the eyeballs. Kent Stevens of the University of Oregon took a creative approach to this question by sculpting the heads of several theropod dinosaurs based on their skeletal structure. From there he was able to map their field of vision, including any obstructions such as horns or an especially large snout. He found that *T. rex* had forward-facing eyes and a narrow snout that wouldn't obstruct its view, giving it a visual acuity similar to that of hawks. Unlike the fictional *T. rex* in *Jurassic Park,* a real *T. rex* would not have needed its prey to move to pick it out from the background. Deinonychosaurs such as *Troodon* and *Velociraptor* were probably even more adept at identifying their prey. With their heads slightly tilted forward, they had wider fields of vision and enhanced depth perception potentially rivaling that of owls.

We can infer more than the ability to perceive depth from the orbits of extinct animals. The size of these openings and their associated bones provide hints about the size of the eyeballs they housed. Larger orbits typically indicate larger eyeballs. Eyeballs that are large relative to the size of the head are common among nocturnal animals because they can accommodate larger numbers of light-sensitive photoreceptors in the retina. Moreover, the eyeballs of many animals, including fish, some extinct mammals, and reptiles (nonbird dinosaurs and birds among them), have bony or cartilaginous rings embedded within the fibrous outer layer of the eyeball known as the sclera. Because bone is rigid, these scleral rings constrain the movements of the eyeball, including how far the pupil can open. This affects how much light reaches the photoreceptors in the retina. Larger scleral rings allow the pupils to open wider, thereby letting more light into the eye.

A few years ago Balanoff was part of a team led by Jonah Choiniere of the University of the Witwatersrand in South Africa that studied the size of these rings in the orbits of nonbird dinosaurs to determine whether they preferred to move about during the daytime or at night. Because the scleral rings are not attached to any part of the skull, they are easily dissociated from the rest of the skeleton and rarely pre-

Evolving Brains

Scientists use endocasts to study how the brain changes in size and shape over evolutionary time. For instance, in the evolution of birds from nonbird theropod dinosaurs the cerebrum—the seat of cognition—expanded, whereas the olfactory bulbs dwindled. Earlier diverging theropods such as *T. rex* had relatively small cerebrums and large olfactory bulbs that presumably conferred a keen sense of smell. Extinct dinosaurs more closely related to birds, such as *Tsaagan* or *Zanabazar,* tended to have a proportionally larger cerebrum and smaller olfactory bulbs. *T. rex* and birds both had relatively large optic lobes, however, suggesting that birds inherited their sharp eyesight from their theropod ancestors.



served in fossils. In the rare specimens that retain them, they are not always found in place. For this study, the researchers used CT images of extinct dinosaurs with preserved scleral rings to digitally isolate these bones and reconstruct them within the orbit. They concluded that the proportions of their orbits and scleral rings suggest many extinct dinosaurs were active primarily during the daytime.

But one house-cat-size alvarezsaurid theropod, *Shuvuuia deserti,* provided a different result. The team examined a *Shuvuuia* skull discovered in Late Cretaceous desert dune deposits from Mongolia and were startled to find adaptations convergent with one of the best-known living nocturnal animals, the barn owl. Barn owls have large orbits with ample scleral rings, which allow their pupils to open very wide. This arrangement lets an enormous amount of light flood into the eye, providing a picture in the darkest of conditions. The presence of these same features in alvarezsaurids suggests that they, too, were active nighttime predators.

No one has formally analyzed the orbit morphology of *T. rex* for insights into when the dinosaur was most active. We do know, however, that *T. rex* had a large orbit shaped almost like a keyhole. If the eye had filled the entire orbit, then we might be able to infer that *T. rex* was nocturnal, but scleral rings from closely related species suggest that its eyeball filled only a small portion of the orbit—and thus might not have been able to gather enough light to be of much use at night. In fact, digital analyses of skull stresses led by Stephan Lautenschlager of the University of Birmingham in England indicate that the large orbit of *T. rex* helped to disperse the large stresses generated by its forceful bite rather than accommodating a big eye.

NEAR THE REAR of the vertebrate skull is an interesting and complex structure: the inner ear. Though not technically part of the brain, it is an important sensory organ that sends a lot of information to the brain. Two special senses, balance and hearing, are controlled by separate parts of the inner ear's so-called labyrinth. The labyrinth comprises the semicircular canals, looplike structures that detect rotational movement of the head; the vestibule, a bloblike structure that senses back-and-forth and side-to-side movements; and the cochlea, which senses sound vibrations. The inner ear is filled with fluid and uses deflection of hair cells within that fluid to detect these different types of information.

In 2021 Michael Hanson, now at the Smithsonian Institution, and his colleagues carried out a sophisticated analysis of the shape of the semicircular canals and vestibule to infer the dominant mode of locomotion in nonbird dinosaurs. They made virtual endocasts of the inner ear space to estimate what the labyrinth would have looked like during life. Their data indicate that most dinosaurs were restricted to walking and running along the ground. But in the lineage that led to birds, the structure of the ear changed. Among other shifts, the semicircular canals grew longer. This elongation allowed dinosaurs to make and interpret more complex movements of the head. *T. rex* didn't have long semicircular canals, suggesting that it was capable of only walking or running. But some troodontid dinosaurs more closely related to *Velociraptor* had an ear that could sense the complex movements associated with flight. These dinosaurs were probably capable of gliding or a rudimentary form of flight, moving through the air before modern birds took wing.

We can look to the cochlea for clues to dinosaurs' hearing. The length of the cochlea is correlated with hearing sensitivity. A longer cochlear duct allows for an elongation of the basilar papilla, the structure that holds the hair cells that pick up sound vibrations. Lizards and turtles tend to have short, stubby cochleas best suited to detecting low-pitch sounds. Crocodilians and birds, in contrast, have much longer, slenderer cochleas that excel at detecting higher-pitched sounds.

Many birds sing melodious songs to attract mates and defend their territory, so it might seem fitting that they have increased sensitivity to high-pitched vocalizations. Yet the elongation of the cochlea originated not in birds but in the common ancestor of birds and crocodilians. The weird thing is, croc vocalizations are limited to low-pitched, closed-mouth grunts—not the kinds of sounds that an elongated cochlea excels at detecting. Exactly why crocodilians have such an advanced cochlea shape compared with other reptiles was a mystery.

Hanson and his collaborators proposed a clever explanation. They hypothesized that the elongation of the cochlea that differentiates crocodilians, extinct dinosaurs and birds from earlier-diverging reptiles has to do with the evolution of parental care. Unlike most reptiles, crocodilians care for their young. And unlike most young reptiles, crocodilian babies chirp to get their parents' attention. Perhaps the ancestors of birds and crocs needed to be able to detect high-pitched sounds to hear their young rather than mates or rivals.

This hypothesis has exciting implications for the evolution of birdsong. In this scenario, juvenile dinosaurs could have chirped for attention, but adults were restricted to producing simple low-pitched calls. Over the course of the dinosaur-bird transition, some lineages retained the capacity for high-pitched vocalizations into adulthood. Cochlear elongation, originally favored by natural selection for its role in enhancing parental care, then served as a preadaptation that allowed song to arise in later birds.

But evolution doesn't move in a single direction. Sifting through the dinosaur data, Hanson and his colleagues stumbled on an unusually short cochlea in *Alioramus,* a cousin of *Tyrannosaurus.* This discovery suggested that the large theropod had lost sensitivity to higher-pitched sounds. The team speculated that *Alioramus* might have left its young unattended, removing the selection pressure for hearing their vocalizations.

The shape of the cochlea has also helped us understand the ecology of those oddball nocturnal alvarezsaurids. Balanoff and her colleagues found that the cochlea of *Shuvuuia* was so long that it curled under the base of the skull. Nocturnal birds such as owls are known to have a similar arrangement. The hyperelongated cochlear duct of *Shuvuuia* indicates that its hearing was attuned to very high-frequency sounds such as those produced by insects. The team concluded that this small dinosaur prowled the desert dunes of Central Asia in the darkness, hunting for these small prey.

Like modern predators, *T. rex* had a proportionally large brain compared with its plant-eating quarry.

PEOPLE TEND TO THINK of paleontology as a field-based discipline, focusing on the romantic allure of summers spent in remote desert locales with pickax in hand, collecting fossils of long-extinct animals new to science. But these days paleontologists are just as likely to make their most significant discoveries in the laboratory using cutting-edge technologies from biomedicine and neuroscience. It is the combination of these disparate approaches that allows us to reconstruct what really might have gone down when *T. rex* encountered *Triceratops.*

Our own research tells us that like modern predators, *T. rex* had a proportionally large brain compared with its plant-eating quarry. A substantial part of its brain was devoted to olfaction, so *Tyrannosaurus* probably did sniff the air to locate its next meal, whether it was the living *Triceratops* grazing along the tree line or one that was already dead and rotting in the sun. Once the *T. rex* isolated a scent, it could then scan the horizon with its stereoscopic vision for any sign of potential prey. Its eyes would have been able to fix on that *Triceratops* obliviously feeding on a cluster of vegetation far from the safety of its herd.

As the *T. rex* crashed through the trees, it might have startled a small troodontid dinosaur nesting in the branches nearby. With the enhanced locomotor skills afforded by its expanded inner ear labyrinth, the troodontid might have glided off its nest, distracting the predator from its chirping young. Unsettled by this commotion, the *Triceratops* might have stopped its peaceful grazing and returned to the safety of its herd. It's still a clichéd story but one that is much more scientifically informed. ⬢

FROM OUR ARCHIVES
Rise of the Tyrannosaurs. Stephen Brusatte; May 2015.
ScientificAmerican.com/archive

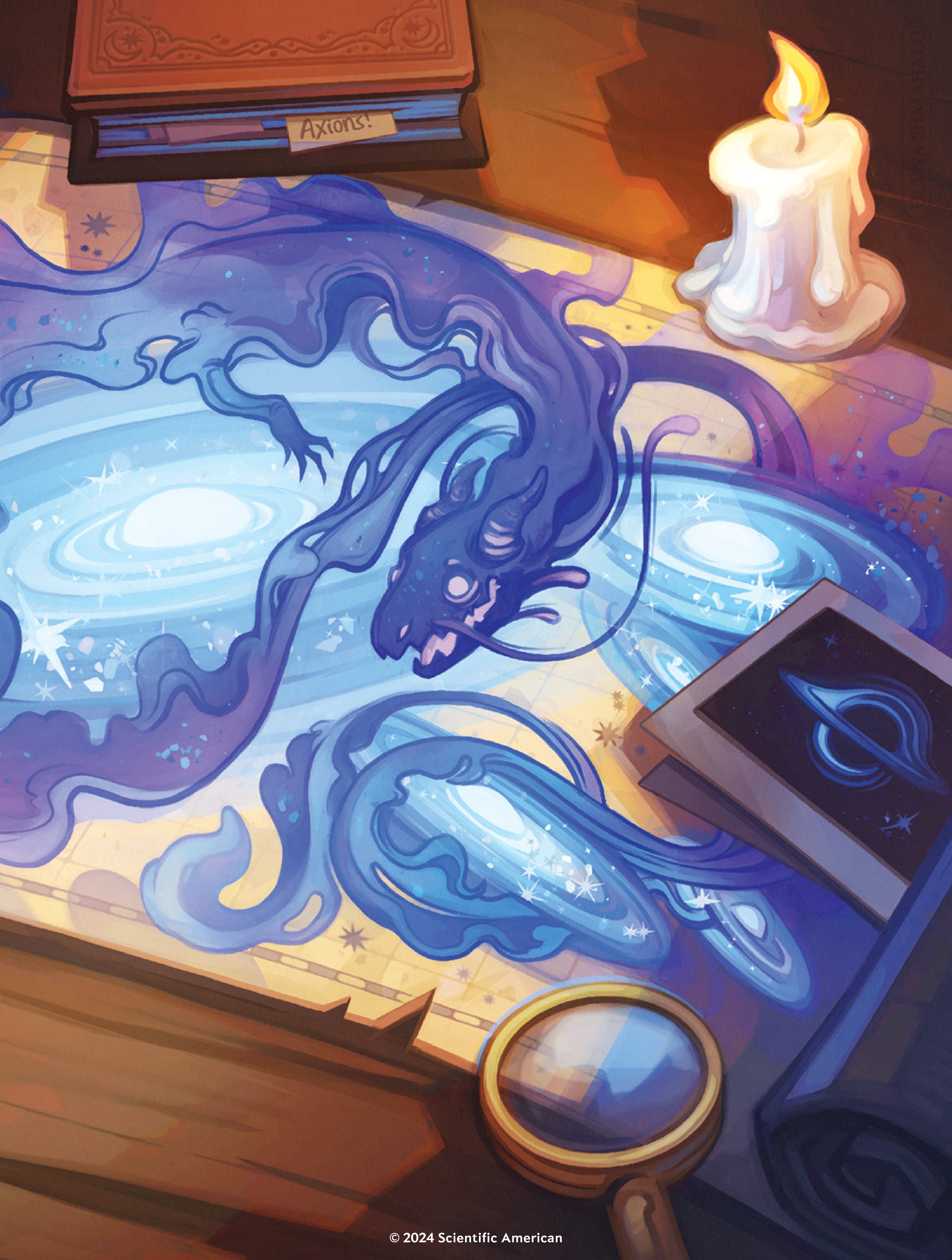
ASTROPHYSICS

What If We Never Find Dark Matter?

Physicists are chasing an increasingly elusive quarry

BY TRACY R. SLATYER AND TIM M. P. TAIT

ILLUSTRATION BY OLENA SHMAHALO


Axions!

MOST OF THE MATTER IN OUR UNIVERSE IS INVISIBLE. We can measure the gravitational pull of this "dark matter" on the orbits of stars and galaxies. We can see the way it bends light around itself and can detect its effect on the light left over from the primordial plasma of the hot big bang. We have measured these signals with exquisite precision. We have every reason to believe dark matter is everywhere. Yet we still don't know what it is.

Tracy R. Slatyer is a theoretical astroparticle physicist at the Massachusetts Institute of Technology. She studies the nature of dark matter.

Tim M. P. Tait is a theoretical high-energy physicist at the University of California, Irvine. His research focuses on particle physics, cosmology and the search for dark matter.

We have been trying to detect dark matter in experiments for decades now, to no avail. Maybe our first detection is just around the corner. But the long wait has prompted some dark matter hunters to wonder whether we're looking in the wrong place or in the wrong way. Many experimental efforts have focused on a relatively small number of possible identities for dark matter—those that seem likely to simultaneously solve other problems in physics. Still, there's no guarantee that these other puzzles and the dark matter quandary are related. Increasingly, physicists acknowledge that we may have to search for a wider range of possible explanations. The scope of the problem is both intimidating and exhilarating.

At the same time, we are starting to grapple with the sobering idea that we may never nail down the nature of dark matter at all. In the early days of dark matter hunting, this notion seemed absurd. We had lots of good theories and plenty of experimental options for testing them. But the easy roads have mostly been traveled, and dark matter has proved more mysterious than we ever imagined. It's entirely possible that dark matter behaves in a way that current experiments aren't well-suited to detect—or even that it ignores regular matter completely. If it doesn't interact with standard atoms through any mechanism besides gravity, it will be almost impossible to detect it in a laboratory. In that case, we can still hope to learn about dark matter by mapping its presence throughout the universe. But there is a chance that dark matter will prove so elusive we may never understand its true nature.

ON A WARM SUMMER EVENING in August 2022 we huddled with a few other physicists around a table at the University of Washington. We were there to discuss the culmination of the "Snowmass Process," a year-long study that the U.S. particle physics community undertakes every decade or so to agree on priorities for future research. We were tasked with summing up the progress and potential of dark matter searches. The job of communicating just how many possibilities there are for explaining dark matter, and the many ideas that exist to explore them, felt daunting.

We are at a special moment in the quest for dark matter. Since the 1990s thousands of investigators have searched exhaustively for particles that might constitute dark matter. By now they've eliminated many of the simplest, easiest possibilities. Nevertheless, most physicists are convinced dark matter is out there and represents some distinct form of matter.

A universe without dark matter would require striking modifications to the laws of gravity as we currently understand them, which are based on Einstein's general theory of relativity. Updating the theory in a way that avoids the need for dark matter—either by adjusting the equations of general relativity while keeping the same underlying framework or by introducing some new paradigm that replaces general relativity altogether—seems exceptionally difficult.

The changes would have to mimic the effects of dark matter in astrophysical systems ranging from giant clusters of galaxies to the Milky Way's smallest satellite galaxies. In other words, they would need to apply across an enormous range of scales in distance and time, without contradicting the host of other precise measurements we've gathered about how gravity works. The modifications would also need to explain why, if dark matter is just a modification to gravity—which is universally associated with all matter—not all galaxies and clusters appear to contain dark matter. Moreover, the most sophisticated attempts to formulate self-consistent theories of modified gravity to explain away dark matter end up invoking a type of dark matter anyway, to match the ripples we observe in the cosmic microwave background, leftover light from the big bang.

In contrast, positing a new type of matter that simply doesn't interact with light is a simple idea. In fact, we already have an example of such dark matter in the form of neutrinos—nearly massless particles that are ubiquitous but rarely interact with other matter. It's just that we already know neutrinos can't account for most of the dark matter in the universe. At most, they can make up about 1 percent of it.

So what about the other 99 percent? Could dark matter be the tip of an iceberg of discovery, the first revelation of one or more new particles that aren't part of the Standard Model of particle physics? Could dark matter feel new forces that the known particles do not (in the same way that dark matter doesn't appear to feel electromagnetic forces), or could it be linked to new fundamental principles of nature? Could dark matter solve outstanding puzzles lurking within the well-measured physics of the Standard Model, or could it reveal the earliest moments of the universe's history? Right now the answers to all these questions are a definitive "maybe"—but the potential power of such a discovery drives us onward.

TWO OF THE MOST POPULAR proposals for the identity of dark matter are the weakly interacting massive particle (WIMP) and the axion of quantum chromodynamics (QCD). These ideas have shaped how theorists think about dark matter and inspired many of the experiments searching for it.

WIMPs are hypothetical stable particles with masses comparable to those of particles in the Standard Model. A proton's mass is just under 1 GeV/c^2, and most WIMP searches have focused on the mass range between 10 and 1,000 GeV/c^2. (Particle physicists find it convenient to measure masses in units of energy using Einstein's $E = mc^2$.) The classic version of a WIMP is a new particle that interacts directly with the W and Z bosons known to carry the weak nuclear force (hence the "W" in WIMP). Such particles appear naturally in models of supersymmetry, where every known particle also has a heavier counterpart called a superpartner. A decade and a half ago our field hoped that the Large Hadron Collider near Geneva would find superpartners, but we had no such luck. If supersymmetry exists, the superpartners must be heavier than we'd initially expected. Furthermore, although many versions of supersymmetry predict WIMP dark matter, the converse isn't true; WIMPs are viable dark matter candidates even in a universe without supersymmetry.

The scope of the dark matter problem is both intimidating and exhilarating.

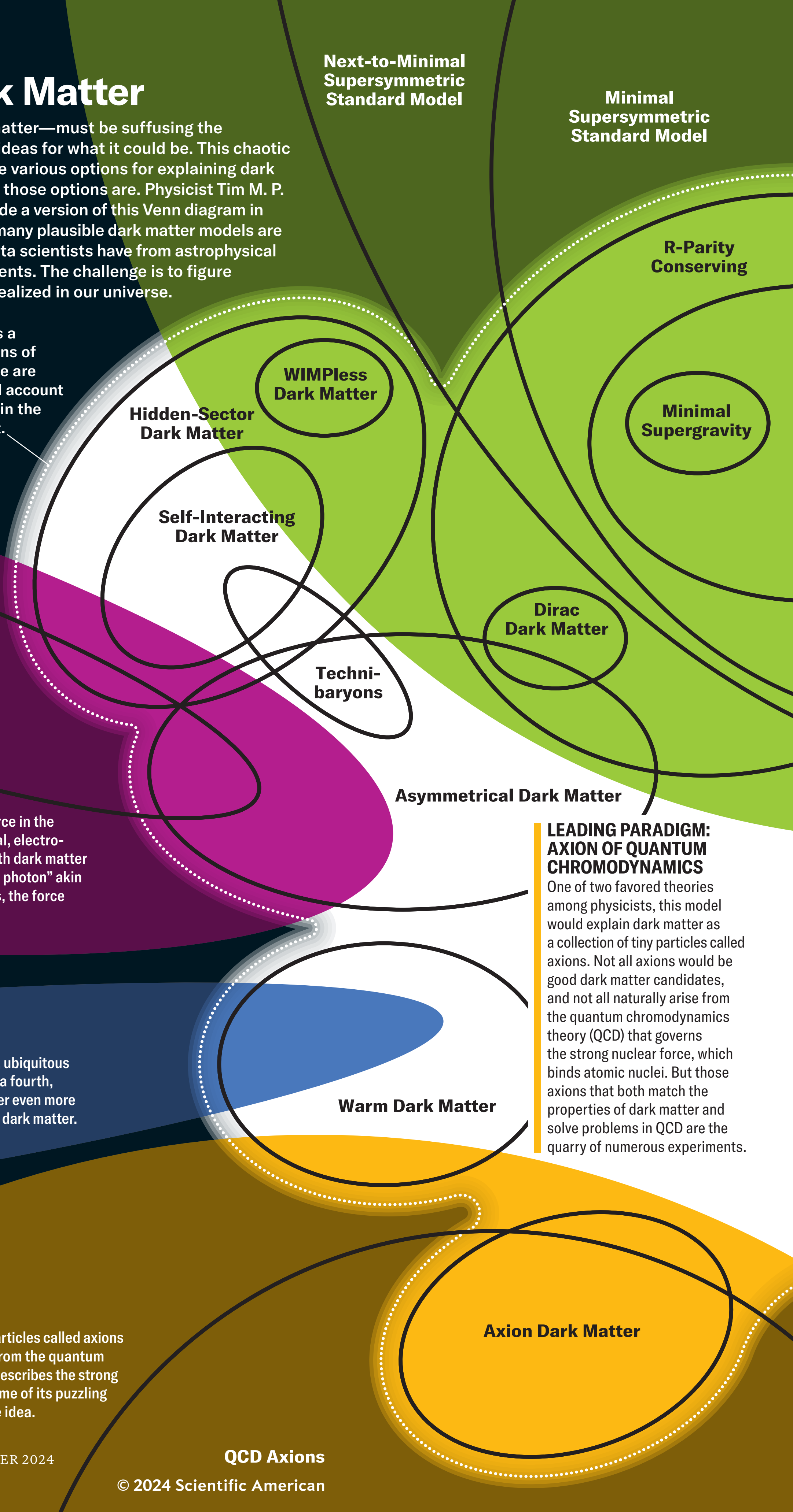
One of the reasons many physicists love the WIMP idea is that these particles naturally would have generated the same amount of dark matter in the universe that we observe. As the thinking goes, when the cosmos was much smaller, denser and hotter than it is now, even weak interactions were enough to produce WIMPs when known particles collided. And a similar reaction happened in reverse—when WIMPs collided, they created regular particles. If the big bang hadn't produced WIMPs originally, the known particles would have made them. And collisions of WIMPs that transmuted their energy into known particles would have destroyed most WIMPs, leaving only a residual abundance. A WIMP with a mass around that of the Higgs boson would produce the correct amount of dark matter, for instance. This mechanism is simple and appealing.

WIMPs appeal to many experimentalists because they must interact significantly with the known particles—that's how they arrive at the right amount of dark matter. There are three classic ways to search for WIMPs: collider experiments, where we hope to reproduce the conditions of the early universe by colliding Standard Model particles together to generate dark matter; direct-detection experiments, which use extremely sensitive detectors to look for visible particles "jumping" when they are struck by a dark matter particle; and indirect detection, where we look out into space to search for familiar particles being produced when dark matter particles collide and annihilate one another. The third approach in particular tests exactly the same destructive processes that would have set the abundance of WIMPs in the universe. Therefore, if these reactions behave in the same way today as they did in the early universe, we have a definitive prediction for how often

Theories of Dark Matter

Some kind of invisible mass—dark matter—must be suffusing the universe, and scientists have lots of ideas for what it could be. This chaotic web of overlapping ellipses shows the various options for explaining dark matter and reveals just how complex those options are. Physicist Tim M. P. Tait, co-author of this article, first made a version of this Venn diagram in 2013. This updated chart shows that many plausible dark matter models are still viable and consistent with the data scientists have from astrophysical observations and laboratory experiments. The challenge is to figure out which, if any, of these ideas are realized in our universe.

Each colored bubble represents a category of theories. The portions of the bubble inside the dotted line are versions of the theory that could account for dark matter, whereas those in the areas outside the line could not.

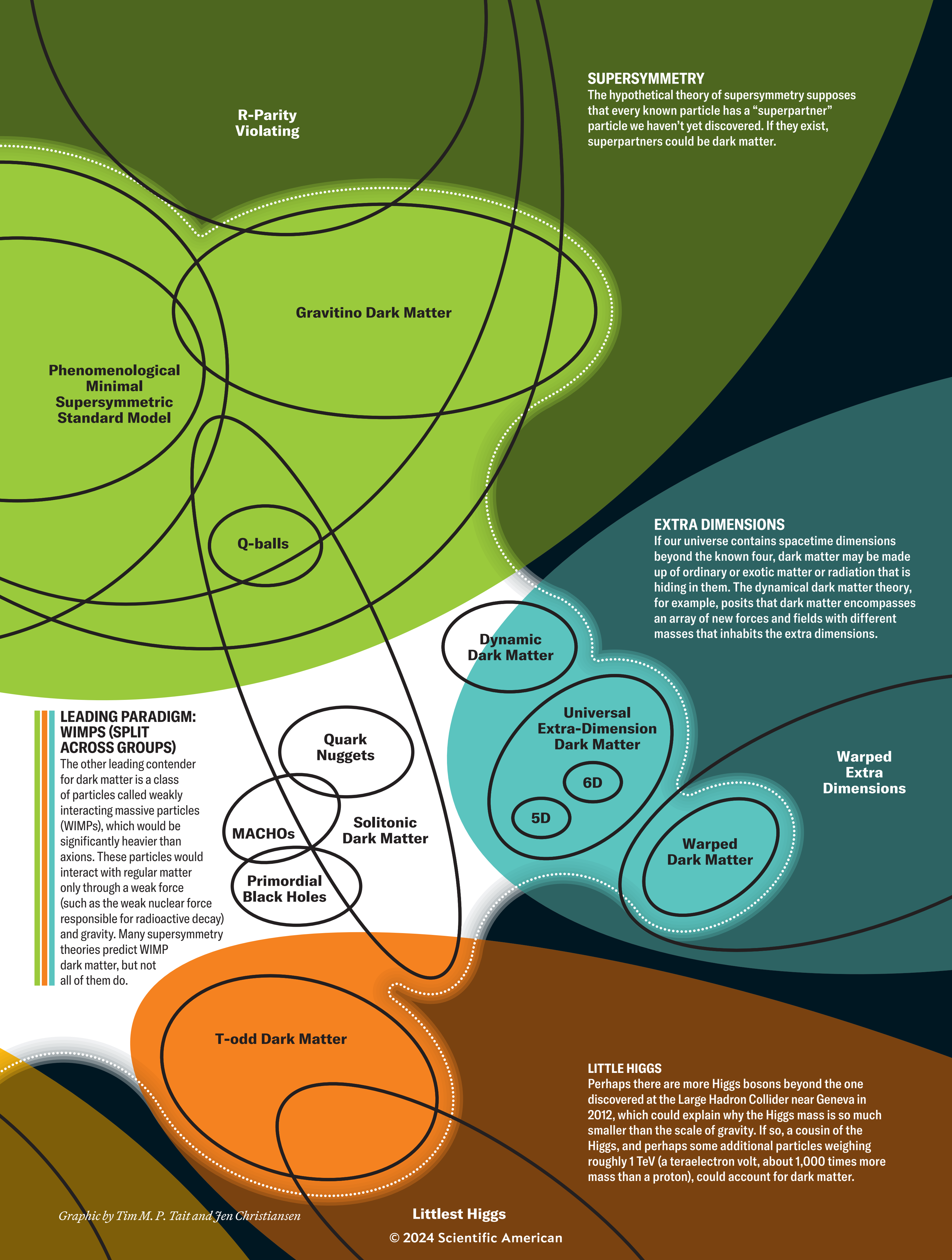


LIGHT FORCE CARRIERS
These models suppose that there is a new force in the universe beyond the known four (gravitational, electromagnetic, strong and weak) that interacts with dark matter and is carried by a lightweight boson—a "dark photon" akin to electromagnetism's photon. In some cases, the force carrier could itself be the dark matter.

STERILE NEUTRINOS
There are three known flavors of neutrinos—light, ubiquitous particles made in stars and other phenomena. If a fourth, "sterile" neutrino exists that ignores normal matter even more than the regular neutrinos do, it could account for dark matter.

AXIONLIKE PARTICLES
This category includes lightweight particles called axions that naturally arise as a possibility from the quantum chromodynamics (QCD) theory that describes the strong nuclear force. They could explain some of its puzzling features, as well as variations on the idea.

LEADING PARADIGM: AXION OF QUANTUM CHROMODYNAMICS
One of two favored theories among physicists, this model would explain dark matter as a collection of tiny particles called axions. Not all axions would be good dark matter candidates, and not all naturally arise from the quantum chromodynamics theory (QCD) that governs the strong nuclear force, which binds atomic nuclei. But those axions that both match the properties of dark matter and solve problems in QCD are the quarry of numerous experiments.



SUPERSYMMETRY
The hypothetical theory of supersymmetry supposes that every known particle has a "superpartner" particle we haven't yet discovered. If they exist, superpartners could be dark matter.

EXTRA DIMENSIONS
If our universe contains spacetime dimensions beyond the known four, dark matter may be made up of ordinary or exotic matter or radiation that is hiding in them. The dynamical dark matter theory, for example, posits that dark matter encompasses an array of new forces and fields with different masses that inhabits the extra dimensions.

LEADING PARADIGM: WIMPS (SPLIT ACROSS GROUPS)
The other leading contender for dark matter is a class of particles called weakly interacting massive particles (WIMPs), which would be significantly heavier than axions. These particles would interact with regular matter only through a weak force (such as the weak nuclear force responsible for radioactive decay) and gravity. Many supersymmetry theories predict WIMP dark matter, but not all of them do.

LITTLE HIGGS
Perhaps there are more Higgs bosons beyond the one discovered at the Large Hadron Collider near Geneva in 2012, which could explain why the Higgs mass is so much smaller than the scale of gravity. If so, a cousin of the Higgs, and perhaps some additional particles weighing roughly 1 TeV (a teraelectron volt, about 1,000 times more mass than a proton), could account for dark matter.

Graphic by Tim M. P. Tait and Jen Christiansen

If we ask, “What could dark matter be?” the possibilities are nearly endless.

they occur. For the first two approaches, the predictions are not so clear-cut. In collider searches, our ability to detect WIMPs depends on how heavy they are: more massive WIMPs may require more energy to produce than the collider has available. And in direct detection, we don’t know how often WIMPs will bump into regular particles.

Astrophysical observations—indirect detection—have revealed several signals that might be hints of dark matter annihilation, but there are also more mundane explanations for what we see. For example, the Galactic Center GeV Excess is a glow of gamma-ray light from the heart of the Milky Way; it has the right rate and the right energy to be a WIMP-annihilation signal. It was discovered in 2009, so why haven’t we declared victory? Unfortunately, we know that certain spinning neutron stars can produce gamma rays at similar energies, and it’s quite possible that the excess is the first sign of a new population of such stars. We hope this question will be resolved in the coming years: finding a counterpart signal in a direct-detection or collider experiment would support the dark matter interpretation, whereas finding radiation from the neutron stars at other wavelengths would rule it out.

In the next decade or so future large gamma-ray telescopes (such as the Cherenkov Telescope Array being built in Chile and Spain and the Southern Wide-field Gamma-ray Observatory planned for somewhere in South America) could test the WIMP mechanism for producing dark matter up to the highest masses where it is viable. Yet even if we don’t observe dark matter annihilation, there are loopholes to save WIMP theory. In some models, the annihilation process that created WIMPs in the early universe switches off at later times. In those cases, however, WIMPs should generally still show up in collider experiments and direct detection.

Direct-detection experiments have made amazing progress in improving their sensitivity to rare events. Within 10 years the next generation of experiments could be so sensitive that they will start detecting neutrinos from the sun streaming through the detector. Until we reach that point, there are no other processes that could masquerade as dark matter, and no seemingly insurmountable technical challenges stand in the way. There are still many simple WIMP models that could show up in this range.

THE QCD AXION IS A VERY DIFFERENT TYPE of dark matter candidate, and until recently we haven’t had nearly the same ability to test it. Like the WIMP, it would be a new fundamental particle, though much tinier: axions are far lighter than any known particle, even neutrinos. If these particles exist—whether they make up all the dark matter or not—they could resolve long-standing puzzles in our understanding of the strong force, which holds atomic nuclei together. Plus, axion theories make distinct predictions: if you know the mass of the axion, you can estimate how strongly it interacts with the known particles. Unfortunately, those interactions depend on the axion mass and can be exceedingly weak for the lighter axions.

Still, axion interactions could have striking effects because to account for dark matter they would have to be so plentiful that they would manifest as a wave rather than as individual particles. According to quantum mechanics, every fundamental particle is also a wave and has an associated wavelength inversely proportional to its mass. At scales smaller than this wavelength, the classical picture of a particle breaks down. Axions are so light that we could expect to see such quantum effects over distances comparable to the typical size of an experiment on Earth.

Because of how weakly QCD axions are expected to interact with regular matter, fewer experiments have looked for them, and they have searched in only a tiny fraction of the possible mass range. New detection strategies and quantum sensor technologies, however, have opened up prospects for hunting the QCD axion over many orders of magnitude in mass. The latest version of a long-running experiment called ADMX-G2 is extremely sensitive, and upcoming projects such as DMRadio promise to greatly extend the search.

Over the next decade dramatic experimental advances will test both the WIMP and the QCD axion over the bulk of their natural mass range for the first time. The theoretical groundwork has been laid, and the plans for experiments are in place. We could leave it at that—there’s a good chance that these strategies will give us the solution.

And yet . . . even though the WIMP and the axion are beautiful ideas, there is no guarantee that the universe conforms to our aesthetic preferences. And if we ask, “What could dark matter be?” the possibilities are nearly endless.

AN ENTIRE LANDSCAPE OF THEORIES manages to describe everything that dark matter needs to do to explain the universe, but each invokes different particles and forces to make it happen. Theorists have thoroughly mapped out which ideas have a hope of working and which ones are inconsistent with observations. Many of the viable hypotheses are surprisingly different from WIMPs or axions. Some, for instance, include massive aggregate objects composed of many tinier constituents—akin to dark matter atoms composed of different dark particles.

There is a limit to how small dark matter particles can be. If they were much lighter than axions—about

25 orders of magnitude lighter than the mass of the electron—their wavelengths could be close to the size of star clusters or small galaxies. If this were the case, the distribution of dark matter and its gravitational footprint would be observably different.

What about the other end of the mass scale? The smallest clumps of dark matter we can directly observe are tens of millions of times the mass of the sun. Individual dark matter particles should be smaller than that, but how much smaller? If dark matter were made of dense, dark objects—often called massive compact halo objects (MACHOs), as a tongue-in-cheek contrast to WIMPs—then their gravity could deflect light and disrupt orbits as they barreled through the galaxy in ways we could see. MACHOs could take the form of tiny black holes, born in the first moments after the big bang. These black holes would not form from stars—because dark matter predates stars—and could be much lighter than the sun. The only way these black holes could account for all of the dark matter would be if they had about the same mass as the asteroids in our solar system, between around 100 billion and 100,000 trillion metric tons. That would give them individual masses one one-thousandth of the mass of the moon, making them 75 orders of magnitude heavier than the smallest possible dark matter particles. (For comparison, the ratio between the radius of our observable universe and the radius of a proton is only about 41 orders of magnitude.) That's quite a lot of ground to cover.

And in the vast region between these two extremes, we have a plethora of options. The process that could produce WIMPs in the early universe would also work for many other particles. If dark matter were lighter than a proton and born through this mechanism, it could be just one of many new particles inhabiting a "dark sector" of physics. These other particles would generally be unstable, so there would be very few of them out in space. Yet they could show up in particle accelerators, especially if they were also relatively light. Light dark matter and dark sectors could also exist without relying on the WIMP mechanism to produce the right amount of dark matter—there are myriad other possibilities for how to generate the observed abundance of dark matter.

If the dark sector is out there, we need new experimental methods to find it. Classic WIMP detectors, for instance, lose sensitivity once the dark matter is much lighter than atomic nuclei because they look for a strong "kick" on nuclei by incoming dark matter. New technology can seek signs of electrons (which are 2,000 times lighter than protons) being kicked instead or use even more creative strategies to detect tiny energy transfers from dark matter to standard particles. The recent advent of ultrasensitive quantum sensors could help.

The only way we know to search over such a wide range of possibilities is to build many small experiments, each sensitive to different types of dark matter, rather than focusing our resources on a few huge projects. We can also use these small experiments to develop new technologies and try out novel ideas; if one of those strategies proves powerful or detects something that could be an initial hint of dark matter, we could then scale it up.

Indirect-detection searches in space already span a vast range of energy scales. If the dark matter were slowly decaying into visible particles, with a typical lifetime as long as a billion times the current age of the universe, we would know it by now for many possible dark matter masses. We can test primordial black holes, for instance, with this kind of search; this is how we know that if black holes make up all the dark matter, they can't be lighter than about 100 billion metric tons (lighter black holes decay faster).

And even if we don't see a signal, we'll continue to learn more about dark matter by mapping its gravity in space. Current and upcoming instruments will measure the distribution of stars and distant galaxies with fantastic precision and depth. Developments in precision cosmology and artificial intelligence are driving techniques to help us glean as much as we can from these data. Such observations could provide new clues to the fundamental nature of dark matter that will complement what we can learn in the lab.

AFTER ALL THE SNOWMASS DISCUSSIONS, the physics community opted to embrace a balanced strategy. We plan to delve deeply into our favorite theories of dark matter while also searching widely (at a shallower level) to explore as many possibilities as we can.

If we are lucky, one of these experiments will make a clear detection. Once that happens, it will trigger a paradigm shift. The broad and varied search will collapse to focus on that signal, and we'll plan future experiments to better understand it. A discovery would also prompt theorists to study the bigger picture of how to connect dark matter with the rest of the particle zoo we're familiar with.

But what if none of these experiments finds a signal? Perhaps physicists at the next Snowmass Process, about a decade hence, will have to use null results to chart the direction for future searches. We can't deny this outcome would be disappointing, but it would still count as a major achievement. Science moves forward one step at a time, and the results that teach us where not to look for the next insights are just as important as those that confirm a particular idea is correct. If we could predict with certainty what dark matter will turn out to be, it would mean that we already know the answer, making our jobs much less exciting. And although we can't say exactly when or even whether we'll find dark matter, we know that the universe is filled with it. We're optimistic that the next years of our quest will lead us to a deeper understanding of what it is. ⬢

FROM OUR ARCHIVES
Scanning the Cosmos for Dark Matter. Chanda Prescod-Weinstein; April 2022. ScientificAmerican.com/archive

TECHNOLOGY

OUT OF THIN AIR

Tech firms, oil companies and the U.S. government are investing billions of dollars in technology to suck CO_2 out of the atmosphere. Can it save the warming world?

BY ALEC LUHN

PHOTOGRAPHS BY SPENCER LOWELL

Pulverized lime (*white*) on plastic trays at the Heirloom Carbon pilot plant in California's Silicon Valley absorbs carbon dioxide from the air.

O NE EVENING IN LATE 1997, 11-year-old Claire Lackner walked into her dad's study looking for an idea for an experiment for her sixth-grade science class. Her dad, Klaus Lackner, happened to be a physicist working on nuclear fusion at Los Alamos National Laboratory. He'd grown skeptical that fusion could replace dirty fuels and had started thinking about how to take greenhouse gases out of the atmosphere instead. So he suggested Claire try to capture carbon dioxide from air. She bought an aquarium pump and bubbled air through a test tube of sodium carbonate, a base, which bonded with the acidic CO_2 in the airstream, removing about 10 percent of it overnight. Claire won a prize at the county science fair, and her father later wrote a paper arguing that extracting CO_2 from air "has a reasonable probability of success" at reducing global warming.

Scientists had known since the 1950s how to strip CO_2 from the air inside submarines and spaceships to keep the crews from suffocating. But Lackner's paper was the first to argue that we could strip it from the atmosphere to keep Spaceship Earth livable. Claire's experiment, he says, showed "it's not all that hard."

Several years later Lackner co-founded a company called Global Research Technologies, and in 2007 it staged the first demonstration of a technology to extract CO_2 from the ambient air, an approach now called direct air capture (DAC). The device was a tall plexiglass box containing plastic sheets that had been coated with a dry CO_2-absorbing resin. The box door opened like a wardrobe's to let air flow across the plastic. When the door shut, the sheets were misted with water, releasing the CO_2, which was captured in a tank to be used in industry or stashed away underground. That same year Virgin Atlantic airline owner Richard Branson announced a $25-million prize for a "commercially viable" technology to remove greenhouse gases from the atmosphere.

Although the chemistry may not be "all that hard," DAC requires a lot of equipment and a lot of energy—and therefore a lot of money. After the 2008 financial crisis hit, Global Research Technologies ran out of funding. Branson never awarded his prize; a spokesperson said in 2010 that none of the 2,500 entries were ready to draw down any significant quantity of CO_2, and he also acknowledged a growing public "unease" about messing with the atmosphere. Although a few start-ups continued developing their technologies and opened small facilities, notably Climeworks in Switzerland and Carbon Engineering in Canada, DAC fell out of the spotlight.

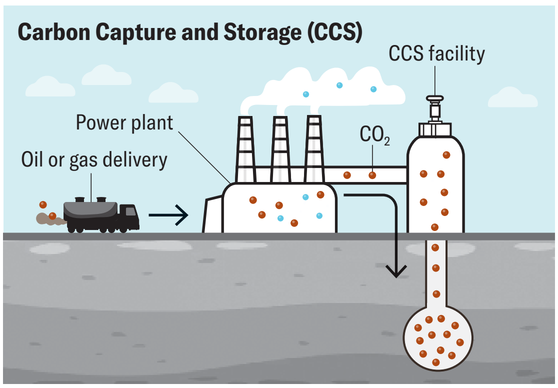
Since the 2000s global emissions have only continued to rise, however, and Earth has gotten hotter. Scientists increasingly recognize that limiting warming to the Paris Climate Agreement goal of 1.5 degrees Celsius above preindustrial temperatures will require more than drastically cutting emissions—it will involve pulling hundreds of billions of tons of CO_2 out of the atmosphere this century. The most obvious way is planting trees. But even a trillion trees would not be nearly enough, and trees can burn or die of disease,

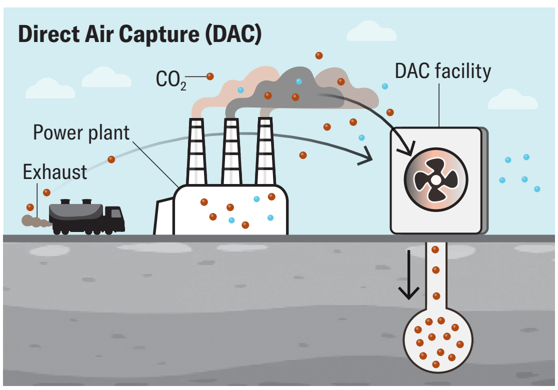
Alec Luhn
wrote the feature "Rusting Rivers" in our January issue. He is an award-winning climate journalist who has reported from a town invaded by polar bears, the only floating nuclear power plant and the coldest inhabited place on Earth.

Limestone is the key ingredient in Heirloom's direct-air-capture process.

emitting the carbon they've stored. In the 2000s the world wasn't ready for DAC, Lackner says. "Now I think we are too late to do without it."

For its goal of reaching net-zero emissions by 2050, the Biden administration is trying to slash carbon pollution by building renewables, electrifying everything from cars to home heating, and encouraging carbon capture and sequestration at power plants. But emissions that are difficult to eliminate, such as those from long-distance air travel, shipping, agriculture, and cement and steel production, will probably have to be removed from the atmosphere, so the government is trying to ramp up DAC. Humans built machines that made a mess; now we'll build more machines to clean it up. And if the world could start taking more emissions out than it's putting in—so-called negative emissions—carbon removal could even begin lowering the global temperature slightly.





The U.S. plans to draw down and store more than a billion tons of CO_2 annually by 2050, more than one fifth of what it currently emits. For that to be possible, carbon removal would have to become one of the world's largest industries in just a few decades, expanding by more than 40 percent each year. That's far faster than most technologies develop—although it is comparable to the pace of solar panels and electric vehicles. "It'd be one of the biggest things humans have ever done," says Gregory F. Nemet, a professor of public policy at the University of Wisconsin–Madison, who wrote a book called *How Solar Energy Became Cheap*. "One of the hardest things we've ever done. But not unprecedented."

Key climate laws in 2021 and 2022 included a major tax break for DAC and $3.5 billion in funding to build several regional DAC hubs. Meanwhile, big companies started looking to purchase carbon removal credits to offset their carbon footprint. A business can buy a credit for one metric ton of CO_2 that a DAC firm sequestered instead of reducing its own emissions by that amount. To this end, more than 130 commercial DAC plants have been proposed in the U.S. Almost all those plants, however, are planned by an oil company that injects CO_2 underground to squeeze out more crude oil from old deposits. U.S. Secretary of Energy Jennifer Granholm has described DAC as "giant vacuums that can suck decades of old carbon pollution straight out of the sky." But now the question is, Could it also end up putting new carbon pollution into the atmosphere?

EARLIER THIS YEAR I DROVE AN HOUR east of San Francisco to visit America's first commercial DAC plant, which Silicon Valley start-up Heirloom Carbon had inaugurated with Secretary Granholm in the farm fields outside Tracy, Calif. After I listened to a safety briefing and put on a hard hat, Heirloom CEO Shashank Samala, a trim, bearded man with a quick grin, took me behind the white mesh netting that surrounded the heart of the plant.

Inside, the operation resembled an oversized industrial kitchen. Hundreds of plastic trays holding what looked like white flour were stacked in 12-meter towers. Rectangular robots moved up and down vertical girders between the towers, checking the flour, which was actually pulverized lime. The lime absorbs CO_2 from air passing over the tray, forming calcium carbonate—limestone powder—over the course of about three days. Then a larger, wheeled robot with a forklift pulls trays from the bottom of a stack and dumps the powder into a duct leading to a 900-degree-C kiln outside. When heated, the limestone releases CO_2 and turns back into lime. The CO_2 is compressed and pumped into a big tank. Later it will be injected underground or mixed into wet concrete, locking the carbon away for centuries. The lime goes back onto the trays to soak up more CO_2.

Samala grew up in an 18-square-meter house in Hyderabad, India, where his mother hung a wet towel over a fan to try to keep the family cool during heat waves. His father worked in the U.S. at a Dippin' Dots ice cream stand and then a pharmacy, and he brought the family to Maine when Samala was 12. After studying economics and robotics at Cornell University and working at the payment company Square, Samala co-founded a company in San Francisco in 2013 that built and delivered custom circuit boards within days.

But Samala was growing concerned about climate disasters, including in India. The 2018 report by the Intergovernmental Panel on Climate Change (IPCC), which for the first time said carbon removal would probably be required to keep global warming to 1.5 degrees C, convinced him that "there is no future

Graphic by Shuyao Xiao

of the planet" without the technology. Two years later he founded Heirloom with Noah McQueen, a chemical engineering Ph.D. student. They developed an approach they could scale up to hundreds of plants, ditching the chemical solvents, intricate filters and high-powered fans of other DAC start-ups in favor of cheap limestone and gentle airflow.

Around the same time, big tech firms were starting to invest in carbon removal, sometimes with the goal of offsetting their own considerable emissions. Within months after Heirloom announced its technology on paper, online retail-services companies Stripe and Shopify committed to pay it hundreds of thousands of dollars for future CO_2 credits, their own effort to help kick-start the demand for carbon removal. The next year Heirloom raised $53 million from a group of investors that included Bill Gates's Breakthrough Energy Ventures, and it won a $1-million preliminary award in Elon Musk's $100-million XPRIZE competition to remove 1,000 metric tons of CO_2 a year and "show a pathway" to billions more. The start-up began building the Tracy facility. In August 2023 the U.S. Department of Energy awarded Heirloom and Climeworks—which operates the world's only other CO_2-sequestering commercial DAC facility, on a mountain plateau in Iceland—up to $600 million to build a DAC hub in western Louisiana, along with project manager Battelle. Called Project Cypress, the joint hub is meant to capture a million metric tons of CO_2 a year and inject it underground.

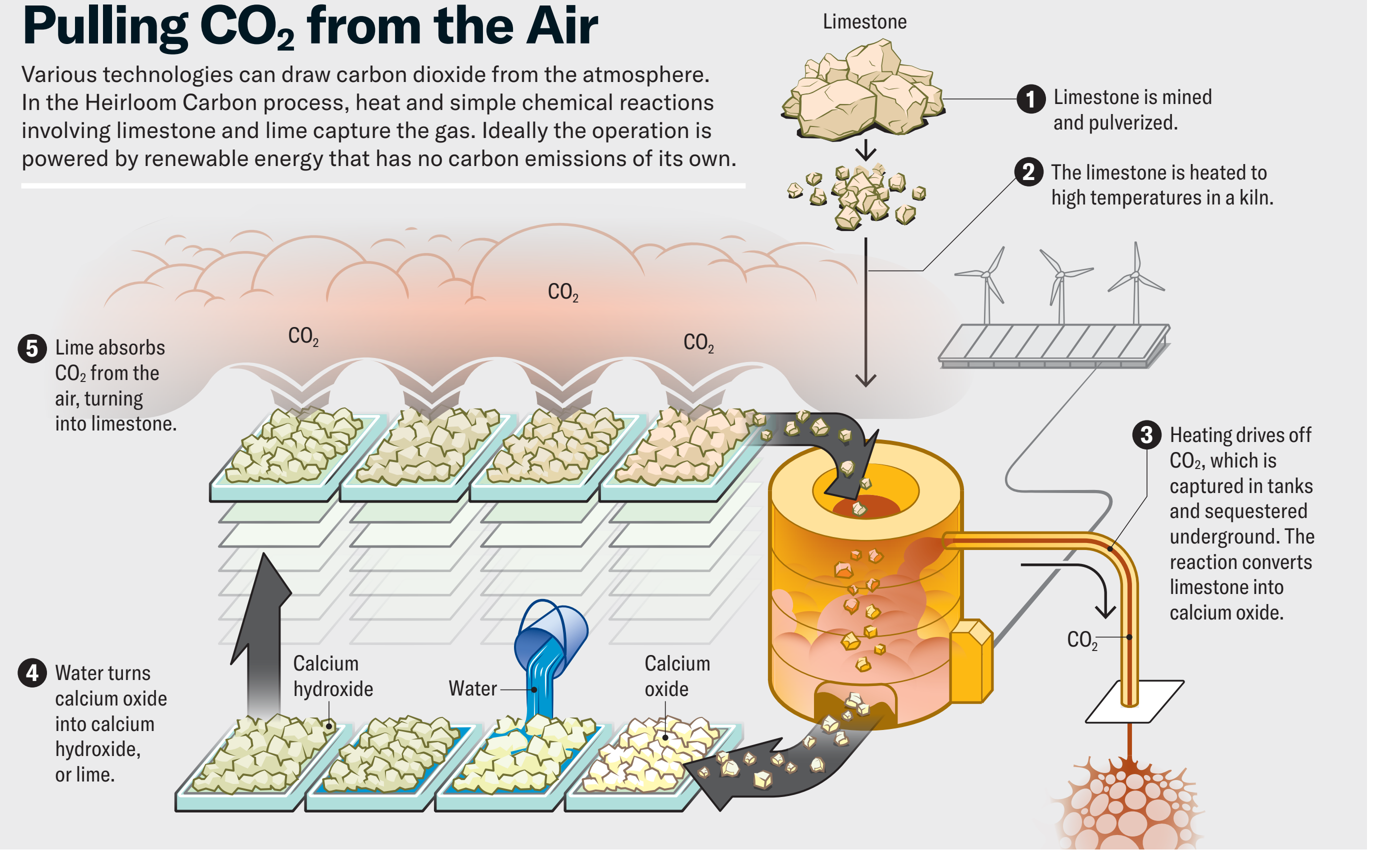
The goal of both the DOE and tech firms, several of which have now pooled $1 billion to invest in carbon removal, is to bring down the price of DAC by bringing up capacity. Right now a credit for removing a metric ton of CO_2 via DAC costs around $1,000, many times more than the equivalent tree planting. But economies of scale can reduce that, according to Samala. "This will come down the cost curve very quickly," he said over the whine of compressors and the cymbal-like crash of a vacuum pump. "You're just putting rocks on trays."

AFTER CALIFORNIA I went to the future site of Project Cypress at Gray Ranch, 400 square kilometers of marshy rangeland on the Louisiana coast, just across the state line from Texas. Driving from Houston to Lake Charles, La., I passed Spindletop Hill, where a 60-meter gusher kicked off the Texas oil boom in 1901. About half of Gray Ranch's income still comes from leasing land for timber, ranching and oil extraction, says family scion Gray Stream, a wiry, blond man who was waiting for me at his colonnaded historic mansion in boots, jeans, a monogrammed blue shirt and a big pelican belt buckle. But he hopes that carbon sequestration will be its next big business, starting with Project Cypress.

I climbed into a black Cadillac Escalade with Stream and four employees for the 50-kilometer drive to the site. We got out on a gravel road next to a grassy field, with an oil well not far in the distance. As we

Pulling CO_2 from the Air

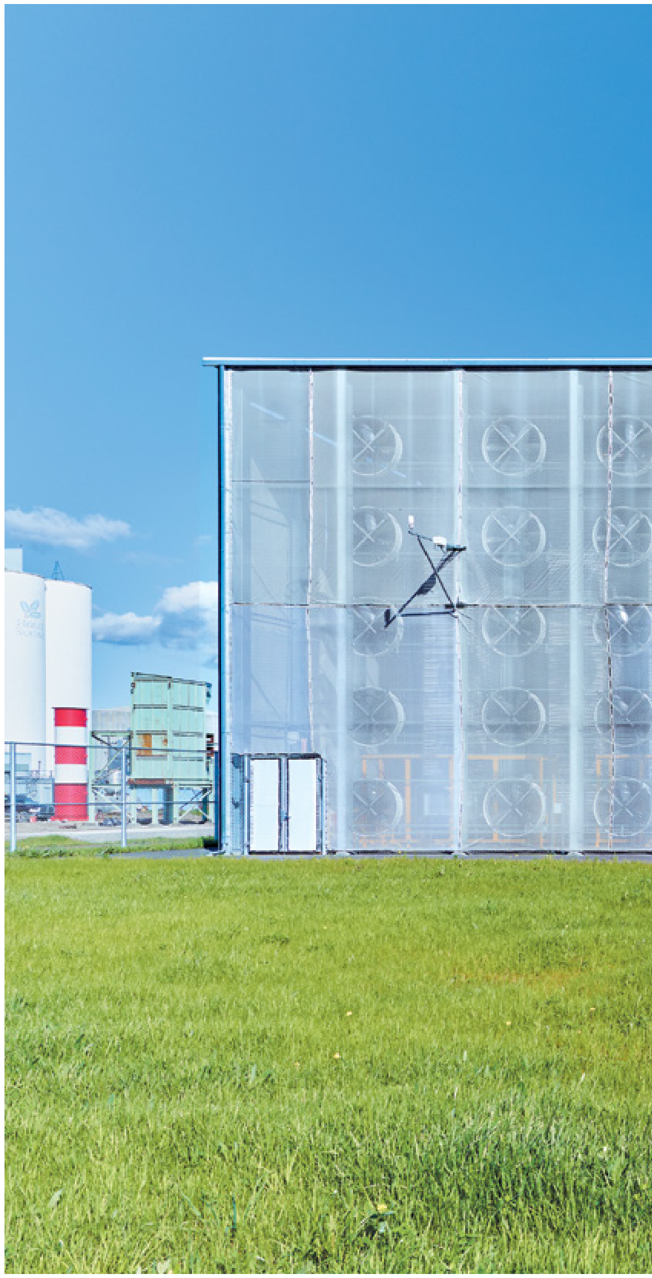
Various technologies can draw carbon dioxide from the atmosphere. In the Heirloom Carbon process, heat and simple chemical reactions involving limestone and lime capture the gas. Ideally the operation is powered by renewable energy that has no carbon emissions of its own.



talked, mosquitoes and turkey vultures began to circle. Within three years this spot will look more like a science-fiction movie set than a cow pasture. Climeworks's latest technology is a cube 23 meters on edge with mesh sides, rounded corners and 16 fan nozzles sticking out of the top, lifted off the ground by massive concrete feet. Some 60 cubes will stand in rows, connected by compressors and pipes. Inside each cube 16 vented boxes will contain filters coated with an ammonia-derived sorbent, which will capture CO_2 from air pulled through the mesh walls by the fans. When the boxes are closed and filled with 100-degree steam, the CO_2 will be released into pipes for sequestration. From the pasture the captured CO_2 will be pumped about 11 kilometers to another part of the ranch, where Stream's team will inject it deep underground. Heirloom was going to build a plant here next to Climeworks, but after I visited, it moved its part of Project Cypress north to be near another facility it is developing in Shreveport, La., which will sequester CO_2 under a timber plantation in central Louisiana.

We got back in the Escalade to drive to the sequestration site, keeping an eye out for alligators. After 20 minutes we arrived at another grassy field between a barge canal and a derelict windmill. Stream got the idea to inject carbon here in 2018, after nongovernmental organizations, energy companies and senators from fossil-fuel states banded together to more than double a tax break known as 45Q. That allowed companies such as the Gulf Coast's natural gas and petrochemical producers to receive a tax credit of up to $50 for every metric ton of CO_2 they captured with scrubbers on their smokestacks and sequestered underground, a process known as carbon capture and sequestration. In 2022 a coalition including Senator Joe Manchin of West Virginia, the senate's top recipient of oil and gas donations, helped increase 45Q to $85 per metric ton of CO_2 captured from a smokestack and $180 per metric ton captured via DAC. For each metric ton they remove in Project Cypress, Climeworks and Heirloom can claim that tax credit while also selling a carbon credit to customers who want to offset their emissions—all while the DOE matches up to $600 million of their investment in the project. To sequester the CO_2, Climeworks will pay Stream, whose ranch sits over a "birthday cake" of rock layers perfect for trapping it underground. "The geology is the magic," Stream says.

That geology began to form 65 million years ago, when the Rocky Mountains surged upward and rivers such as the young Mississippi began to carry grains of crushed sand downhill to the Gulf of Mexico. Through the eons new layers of sediment piled on, and under their weight the older ones below were compressed into porous sandstone. Now and then sea levels would rise, depositing a muddy layer that became shale rock. In places like Gray Ranch, a shale layer forms a dome of impermeable "cap rock" that can seal off CO_2 injected through a well into the sandstone pores below. This layering makes the Gulf Coast the "Saudi Arabia of pore space," Stream says, with room for an estimated 100 billion metric tons of CO_2.



If Louisiana approves Stream's well permit, his team will drill down 2,750 meters through the shale and start injecting compressed CO_2 into the sandstone below. Geologists will watch with instrumentation as the plume of superdense CO_2 displaces salt water from the pores and migrates upward into the shale dome, monitoring it to see whether it stays trapped. They plan to inject 100 million metric tons of compressed CO_2 at three sites over 30 years. But modeling the subsurface can be difficult. At a carbon-sequestration project in the North Sea, the plume broke through eight thin shale layers before being trapped by a previously undiscovered ninth layer. There are also 120,000 abandoned oil wells in Louisi-

ana that CO_2 could potentially escape through, although Stream says the half a dozen wells near his sequestration site have been properly plugged.

Residents in predominantly Black Lake Charles are concerned, however, about the possibility of a rupture in a pipeline transporting CO_2 to the site. A leak in a multistate network of CO_2 pipelines put 45 people in neighboring Mississippi in the hospital in 2020, and another one in a Lake Charles suburb forced officials to issue a shelter-in-place order this past April. More broadly, they're worried that Project Cypress will help perpetuate a legacy of environmental racism. Every night the area glows orange with the flares of more than two dozen fossil-fuel and petrochemical facilities. Driving back to Stream's lakeside home, we passed the Westlake chemical complex, where a 2022 explosion injured six workers. A chlorine plant next door burned down after Hurricane Laura struck in 2020. Two other plants have been caught leaking ethylene oxide and benzene, chemicals that can cause cancers such as leukemia.

The DAC hubs are required to benefit local communities. But Roishetta Sibley Ozane, a Black environmental justice activist whose children have suffered from asthma and epilepsy possibly linked to pollution, says the DOE consulted Lake Charles residents only after it had already chosen them as "guinea pigs" for an unproven technology. The CO_2 sequestration at Gray Ranch will attract even more gas and petrochemical plants, she fears, because Stream plans to also inject CO_2 captured by scrubbers at industrial facilities. At least a dozen fuel plants with scrubbers have been proposed in Louisiana. "I don't have the answers," Ozane says. "We have to stop what's hap-

Fans behind a mesh wall pull air into the carbon-capture operation when winds are light or stagnant.

Robots deliver trays that have soaked up CO_2 to a kiln that bakes out and collects the gas.

pening right now—and that does not look like putting a giant DAC hub in the communities that are already overburdened with industry."

DAC STILL HAS TO ANSWER the question of who will pay. The DOE estimates that by the time the industry is removing a billion metric tons of carbon from the atmosphere every year, the cost of each ton will fall below $100, which will make it profitable based on the 45Q tax credit alone. An April study by researchers at ETH Zurich, however, projected that DAC would still cost about $360 per metric ton. At that rate the cost to suck up a billion metric tons could be more than 1 percent of the U.S. gross domestic product. And it's hard to imagine even cash-flush tech firms voluntarily spending hundreds of billions of dollars on credits every year. The U.S. government—or at least numerous individual states—will probably have to somehow limit companies' emissions, Nemet says, and force polluters to pay to remove CO_2. California has started: companies that want to sell gasoline and diesel in the state have to either reduce their emissions or buy credits. If approved, Climeworks and Heirloom could sell some of those credits to them.

Alongside equipment, energy is the main cost. The million-metric-ton Project Cypress will consume as much electricity as 230,000 U.S. homes. Removing a billion metric tons would require up to twice the electricity the U.S. generated via renewables in 2023. Even without that extra demand, the U.S. isn't on course to meet its renewable-energy goals. Critics have argued that investments in DAC would be better spent on replacing natural gas and coal power, which still generate most U.S. electricity. Running a DAC plant with wind power would put up to 42 percent more CO_2 in the atmosphere over two decades than replacing a coal plant with that same wind power, according to a 2019 study by Mark Z. Jacobson, a civil and environmental engineering professor at Stanford University. And it wouldn't reduce coal pollutants such as sulfur dioxide. "Until every fossil plant and every bioenergy plant is gone, there's no benefit whatsoever of direct air capture," Jacobson says. "It always increases air pollution, increases CO_2, increases fuel mining, increases fossil infrastructure."

There are also concerns that DAC poses a "moral hazard" for the steep reduction in fossil-fuel use that scientists say is necessary: Why stop burning carbon

Granular lime on the trays turns into limestone in about three days as it reacts with CO_2 in the air.

if you think you can just suck it out of the air later? The world is way behind in meeting the 1.5-degree-C goal, yet major oil and gas countries, including the U.S., are set to increase production through 2050. "The reliance on these future speculative techno fixes delays real climate action right now," says Lili Fuhr, an analyst at the Center for International Environmental Law. In fact, the biggest private investor in DAC is the major U.S. oil company Occidental Petroleum, or Oxy, whose CEO has said the technology means "there's no reason not to produce oil and gas forever."

After Gray Ranch, I drove south along the coast to Corpus Christi, Tex., a mostly Latino city that was once known for its beaches but has become America's biggest oil-exporting port. In addition to Project Cypress, the DOE awarded up to $600 million to a DAC hub being developed here by Oxy. Climeworks and Heirloom have said DAC shouldn't be a reason to expand fossil fuels, but for Oxy it's part of a strategy to sell "net-zero oil." The idea is that emissions from burning newly produced oil would be offset by CO_2 captured by Oxy's DAC operations. Oxy is already building a separate, 500,000-metric-ton DAC plant in West Texas called Stratos and will inject some of the CO_2 it captures there into old oil wells to force out more crude, a practice known as enhanced oil recovery (EOR). Last year Oxy's CEO, Vicki Hollub, said DAC "gives our industry a license to continue to operate for the 60, 70, 80 years that I think it's going to be very much needed."

Fifteen kilometers south of Corpus Christi, past a megachurch, a fireworks store and some Quonset huts, the gravel road came to a "no trespassing" sign. A dozen wind turbines rumbled in the sea breeze. Beyond a line of scrubby mesquite lay King Ranch, an estate larger than Rhode Island that inspired the oil-boom film *Giant* starring James Dean. As soon as next year, Oxy's South Texas DAC Hub will rise from these umber fields. Oxy declined to comment or let me visit the site, but online renderings suggest it will be a set of long buildings with perforated black walls and a line of huge, round fans in their metal roofs. The fans will suck air through the permeable walls, where potassium hydroxide flowing across honeycombed plastic sheets will bond with CO_2 to form a solution of potassium carbonate. Combining that with calcium hydroxide in a "pellet reactor" will generate lime-

The Heirloom direct-air-capture plant could extract 1,000 tons of CO_2 a year. One thousand such plants could remove a million tons, a small start at counteracting the ongoing rise of CO_2 emissions.

stone pellets, which can be heated in a kiln to release CO_2 into rows of tanks behind the buildings.

The hub's development has so far been shrouded in secrecy. On a minibus tour of the historic central part of King Ranch, 40 kilometers to the west in Kingsville, Tex., our guide talked for an hour and a half about its famous racehorses and squat orange cattle. But she redirected my questions about the DAC hub to management, which never replied to my numerous calls and e-mails. The King Ranch Museum archivist said she can't talk without permission. The president of the local chamber of commerce said he had signed a nondisclosure agreement. The county judge, who lobbied for the hub, agreed to an interview with me on two occasions but canceled both times. "I don't know if we're allowed to talk about it," said a worker who was clearing brush near the ranch entrance.

Oxy's Hollub is a villain or a visionary, depending on whom you ask. The Alabama native worked her way up from oil rig engineer, and in 2016 she became the first female CEO of a major U.S. oil company. She started developing Stratos after the U.S. increased the 45Q tax credit two years later. That's partly because Oxy had become the biggest EOR producer in Texas. During EOR, compressed CO_2 displaces oil that's stuck in rock pores, boosting yields by up to 25 percent. Most of the CO_2 is sequestered in the deposit, but consumers eventually burn the oil produced, creating

more emissions. Oxy, which obtains CO_2 mined from natural reservoirs, was searching for other sources.

By obtaining CO_2 via DAC, Hollub realized, the company could have a triple win: take the tax credit, sell carbon credits and produce more oil. After Hollub helped to successfully lobby Congress to raise the credit to $130 per metric ton for DAC plus EOR, she announced Oxy would open 130 DAC plants by 2035. When the DOE selected its South Texas DAC Hub, Oxy bought Canadian DAC technology firm Carbon Engineering for $1.1 billion. It now has an agreement to offer net-zero oil to a South Korean refiner and has sold carbon credits that will not be linked to EOR to companies including Microsoft, Airbus and Amazon.

Chevron and Shell are investing in both oil drilling and DAC, and they have received smaller grants to pursue their own DAC hubs. The DOE says this funding can help scale up the technology for everyone's benefit while shifting the companies away from fossil fuels. "It's giving them an opportunity to pivot," Jennifer Wilcox told me in March, when she was the deputy head of the DOE's Office of Fossil Energy and Carbon Management (she has since left the DOE). "And these are the companies that have the resources and the assets to actually do it."

But Emily Grubert, a University of Notre Dame sociologist who previously worked for the DOE on DAC hubs, says "paying the oil companies to stop doing oil" is fruitless. She and others argue that the carbon-removal industry should be nationalized, with the government limiting emissions and paying for capture, akin to municipal garbage collection for the atmosphere. Activists such as Ozane have called for the hubs to be at least partially owned by communities. Unregulated, for-profit DAC is "going to be captured by the fossil industry," Grubert says.

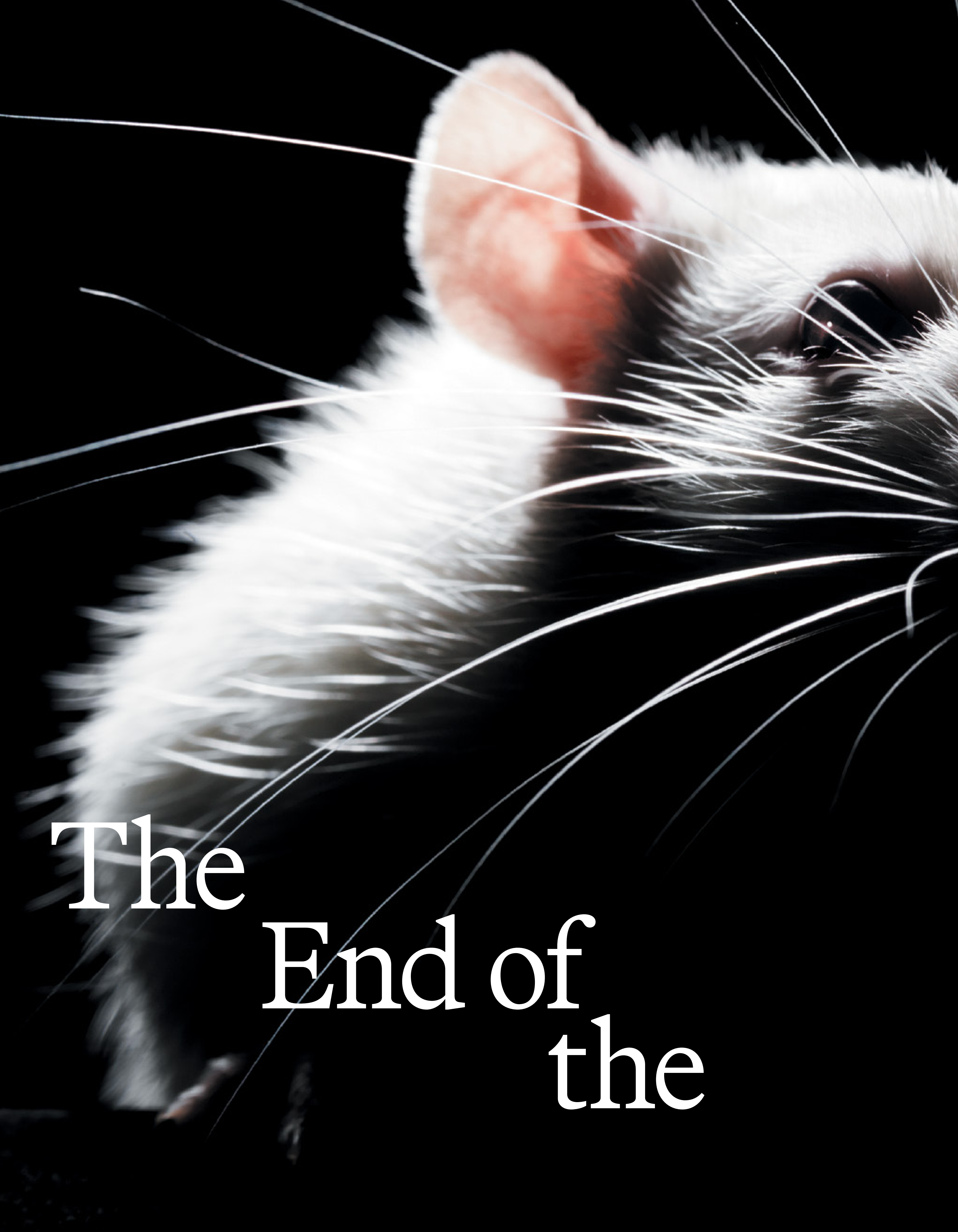
AT THE RIBBON CUTTING for Heirloom's Tracy plant, Samala compared DAC to a time machine that could take us back to an earlier, less screwed-up climate. But for now the DAC time machine is "next to useless," University of Hawaii oceanographer David Ho wrote in *Nature* last year: with humanity emitting 40 billion metric tons of CO_2 a year, the million removed annually by each DAC hub would take us back in time only 13 minutes.

But let's say the nations of the world cut carbon emissions 90 percent by 2050. Several thousand DAC plants running on excess renewable energy could then draw down the final 10 percent to reach net zero. In that scenario, global temperatures would probably peak at 1.6 degrees C above preindustrial levels, according to IPCC modeling.

If we went on to build vast amounts of additional DAC capacity, we could start to turn back the clock on climate change. Taking 220 billion metric tons of CO_2 out of the atmosphere by 2100 would bring temperatures down to about 1.3 degrees C above preindustrial levels, only slightly hotter than today. Deadly catastrophes such as the heat waves in the U.S., the drought in the Amazon, and flooding in Afghanistan and Pakistan this year would continue to happen. But they would happen about half as often as with the 2.9 degrees C of warming we're headed for currently. Done right, carbon removal could also become an instrument for environmental justice, lessening future disasters caused mostly by emissions of the rich and hurting mostly the poor and vulnerable.

For us to have even a shot at that future, we would need to ramp up DAC investment now, Ho says. "If we're leaving future generations all the cumulative emissions in the atmosphere," he says, "it's almost our responsibility to give them a tool to remove it." ●

FROM OUR ARCHIVES
Washing Carbon Out of the Air. Klaus S. Lackner; June 2010. ScientificAmerican.com/archive



The End of the

Millions of animals are used for research purposes every year, but their efficacy is increasingly limited.

Lab Rat?

BIOMEDICINE

Replacing research animals with tools that better mimic human biology could improve medicine

BY RACHEL NUWER

WHEN IT CAME TIME for Itzy Morales Pantoja to start her Ph.D. in cellular and molecular medicine, she chose a laboratory that used stem cells—not only animals—for its research. Morales Pantoja had just spent two years studying multiple sclerosis in mouse models. As an undergraduate, she'd been responsible for giving the animals painful injections to induce the disease and then observing as they lost their ability to move. She did her best to treat the mice gently, but she knew they were suffering. "As soon as I got close to them, they'd start peeing—a sign of stress," she says. "They knew what was coming."

Even though the mouse work was emotionally "very, very difficult," Morales Pantoja remained committed to her research out of a desire to help her sister, who has multiple sclerosis. Three years after the project wrapped up, however, Morales Pantoja was crushed to find that none of her results would be of any direct help to people like her sister. An antioxidant she'd tested seemed promising in mice, but in human samples it was ineffective.

This was a disappointment but not a surprise. Around 90 percent of novel drugs that work in animal models fail in human clinical trials—an attrition rate that contributes to a $2.3-billion average price tag for every new drug that comes to market.

Today Morales Pantoja is a postdoctoral fellow at the Johns Hopkins Center for Alternatives to Animal Testing, where she is helping to develop lab-grown models of the human brain. The goal is to advance scientific understanding of neurodegeneration while moving the field beyond what some researchers see as an antiquated reliance on animal models.

Millions of rodents, dogs, monkeys, rabbits, birds, cats, fish, and other animals are used every year for research purposes worldwide. Exact numbers are hard to come by, but advocacy group Cruelty Free International estimated that 192 million animals were used in 2015. Most of this work occurs in four broad domains: cosmetics and personal products, chemical toxicity testing, drug development, and drug-discovery research.

Animal-based studies have contributed to important findings and lifesaving medical advancements. The COVID vaccines, for instance, were developed in animals, including mice and nonhuman primates. Animal models have also been critical in advancing AIDS drugs and in developing treatments for leukemia and other cancers, among many other uses.

But animal studies often fall short of producing useful results. They may weed out possibly effective drugs or miss toxicity in humans. They have failed to deliver breakthroughs in certain fields of medicine, including neurological conditions. A 2014 study estimated that candidate therapies for Alzheimer's disease developed in animal models have failed in clinical trials about 99.6 percent of the time. "As questions about human biology and variability get more complex, we are bumping up against the limits of animal models," says Paul Locke, an environmental health scientist and attorney at the Johns Hopkins Bloomberg School of Public Health. "The thing you run into with animals—and there's no way to get around this—is that animal biology is just too different from human biology." Other species are no longer providing the insights about human biology—including at the cellular and subcellular levels—that scientists today need to achieve innovation.

A growing, multidisciplinary community of researchers around the world is investigating alternatives to animal models. Some are motivated by concerns about animal welfare, but for many, sparing the lives of millions of creatures is just an added bonus. They are driven primarily to create technologies and methods that will approximate human biology and variability better than animals do.

For the past decade or so dozens of labs, start-ups and nonprofit groups have pursued alternative methods that range from machine-learning tools that predict chemical toxicity to living "organs-on-a-chip" that can be combined to replicate human organ systems. Their efforts have now matured to the point where some labs are phasing animals out entirely. Research is beginning to show that these new methods often provide significantly more accurate answers than animals do.

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Henrik Sorensen/Getty Images (*preceding pages*)

Legislation is beginning to reflect these developments. In 2021 the European Parliament passed a resolution to phase out animal testing in research. Australia's national science agency has begun seriously exploring nonanimal models for medical product development. In 2022 President Joe Biden signed a bill that did away with a long-standing U.S. Food and Drug Administration requirement for animal testing as a part of every new drug application. In May 2023 Maryland passed a first-of-its-kind law mandating that animal-testing labs contribute to a fund that will be directed to other labs developing human-relevant alternatives. Another federal bill, introduced in 2024, would pave the way for the FDA to begin accepting data from new methodologies on a wide scale.

This convergence of developments in legislation, industry and science will bring about "a sea change in how we conduct biomedical research," says Danilo Tagle, director of a group at the U.S. National Institutes of Health that is leading an institution-wide push to invest in alternatives to animal models. This year the NIH is launching a $300-million fund that specifically supports the development, validation and testing of nonanimal alternatives for drug screening, disease modeling, and more. This resource will be on top of the 8 percent of the NIH's $40-billion research budget already awarded for alternative methods, a percentage that has been rising for the past 15 years. As Tagle says, "We're seeing a convergence in legislation, industry and scientific developments."

Paul Locke of Johns Hopkins and others say it's not a question of whether animal testing will be phased out of most research but when.

IN 1937, WHEN 12 PATIENTS came to Archibald "Archie" Calhoun complaining of infections, the physician from Covington County, Mississippi, did what he often did: he wrote them prescriptions for sulfanilamide, an antibiotic he'd used for years. Within days, six of the patients were dead. The pharmaceutical company that produced sulfanilamide had added a new ingredient to the raspberry-flavored formula: diethylene glycol, a type of antifreeze, which turned out to be deadly. "This realization has given me such days and nights of mental and spiritual agony as I did not believe a human being could undergo and survive," Calhoun wrote afterward.

The "sulfanilamide disaster," as the incident came to be known, took the lives of more than 100 people, many of them children. Congress responded with the Federal Food, Drug and Cosmetic Act, a set of laws designed to ensure that no company would ever again unknowingly sell a toxic drug. Among other things, the act required that new drugs in development be tested on animals before being given to humans. "An early success of animal models was to keep these horrible products off the market," Locke says.

Today animal models are still considered the standard for pharmaceutical and drug-discovery research, partly because many people in the scientific community still get value from them and partly because they're the status quo. Yet the full extent of animal use in the U.S. is unknown. Federal laws do not require researchers to make public the number of rats, mice and birds—the three species that make up more than 95 percent of testing subjects—bred for research purposes. Likewise, no comprehensive analyses have tallied the amount of U.S. government–funded research that uses animal models, according to Tagle.

People for the Ethical Treatment of Animals, or PETA, has estimated that just under half of NIH research funding goes toward animal-based studies. Organizations outside of government and academia use animals for research as well. The Humane Society of the United States estimates that more than 50 million animals are used for research purposes every year in the U.S. alone.

Locke and others say it's not a question of whether animal testing will be phased out of most research but when. "Everyone recognizes that the goal is to eventually try to replace animals," says Naomi Charalambakis, associate director of science policy at the Federation of American Societies for Experimental Biology, a nonprofit group that represents 22 scientific societies and more than 110,000 researchers worldwide. But animals are not going to disappear from research soon. "We're still very much in the nascent phases," Charalambakis says.

The Interagency Coordinating Committee on the Validation of Alternative Methods (ICCVAM), which operates under the auspices of the U.S. National Institute of Environmental Health Sciences, is a group of 18 research and regulatory agencies working together to promote new scientifically valid methods that are rooted in human biology and that reduce and replace animal tests. According to Nicole Kleinstreuer, a computational toxicologist and executive director of ICCVAM, the team prioritizes "scientific projects that will ultimately result in regulatory translation and implementation."

How quickly that happens, though, will vary. Locke suspects discovery research—which seeks to understand basic mechanisms of biological systems—will probably take the longest because it is the most complex domain that scientists use animals to explore. For this research, animals offer the advantage of being living creatures with complete organ systems that interact in a coordinated fashion—something that in vitro approaches cannot yet do.

The cosmetics and personal products industry is the furthest along in doing away with animal testing, primarily because of consumer demand. More than 2,500 North American cosmetics, personal care and household product companies are certified as animal-free. Twelve U.S. states and 45 countries have banned animal-tested cosmetics, and legislation reintroduced in the House in September 2023 could add the full U.S. to that list.

Phasing animals out of some types of toxicity testing—carried out to establish a substance's potential to cause harm—is probably next in line. Numerous studies have shown that, in many cases, artificial-intelligence-based algorithms trained with preexisting data are as reliable as or more reliable than animals in predicting toxicity for various chemicals. In 2016 President Barack Obama signed an amendment to the Toxic Substances Control Act directing the Environmental Protection Agency to begin reducing the use of vertebrate animals in toxicity testing and replacing it with alternative methods if scientifically feasible.

The EPA has made some progress toward this goal. In 2018, for example, the agency granted 62 waiver requests for reductions in animals undergoing certain toxicity testing, sparing around 16,500 animals and resulting in savings of about $8.9 million in its first year. In 2024 the EPA published a new framework for assessing eye irritation or corrosion through alternative test methods.

Some environmental groups have opposed a complete transition away from animal testing. As Susanne Brander, an ecotoxicologist at Oregon State University, summarized last year in work published by the Environmental Defense Fund, "the looming concern" is that new methodologies may miss negative effects that animal models would have caught, "potentially allowing toxic chemicals to appear in consumer products or end up in our environment."

Kleinstreuer says she understands why consumer protection groups might be wary about these changes. But she emphasizes that the EPA's motivation in phasing out animal testing "is to actually provide *better* human health protection using the best science that is fundamentally rooted in human biology."

TO SEE WHAT THE FUTURE of human-centric models might look like, I visited Emulate, a biotechnology company in Boston. Emulate specializes in organ chips: flexible polymer platforms, about an inch long, that duplicate human cell and tissue microenvironments.

Sushma Jadalannagari, a tissue engineer, let me play lab tech. Working in a biosafety cabinet, I sucked up trypan blue dye and inserted a pipette tip into a tiny divot in the top of a pristine chip. As I released the fluid, a thin, inky line appeared along a hollow channel that crisscrossed the chip and ended at another opening at the opposite end. A second channel ran below that one, separated from it by a porous membrane.

Real researchers seed this kind of chip's channels not with dye but with human cells. Multiple chips, each lined with different types of organ-specific cells and tissues, can be linked to mimic multiorgan systems, and researchers can run experiments on one or more chips by flowing fluid or air across the cells, exerting mechanical forces on them or adding things such as pharmaceuticals, cigarette smoke, chemicals, viruses or bacteria.

FROM OUR ARCHIVES
From Hamsters to Baboons: The Animals Helping Scientists Understand the Coronavirus. Simon Makin; Scientific American.com, May 14, 2020. Scientific American.com/archive

Emulate's chips can stand in for liver, kidney, colon and duodenum, and the company also offers blank chips that can be customized. Outside researchers have used the chips to create about 70 additional models with cells from their labs. Emulate's customers are pharmaceutical firms, academic labs and government facilities.

Emulate spun out of the Wyss Institute at Harvard University, based on the work of Don Ingber, an animal-loving cell biologist and bioengineer, who began developing in vitro models 40 years ago because he didn't like experimenting on living creatures. "I used to joke that I was raised by dogs, but now a cat rules my life," Ingber says. His work on organ chips was fast-tracked in 2012 when he and his colleagues received a $37-million grant from the Defense Advanced Research Projects Agency to develop the technologies. Ingber is now regularly approached by agencies, foundations and companies with offers to apply for funding.

Emulate is one of a growing number of businesses pursuing alternative methods that scientists can use in their research, a space only five to 10 companies were exploring a decade ago. These tests and devices are not designed to be exact replicas of human organs in healthy or disease states. Nor are they meant to serve as one-to-one replacements of animal models. Rather the goal is to recapitulate functions and features that scientists need to study for a particular problem. A liver chip doesn't have to perfectly simulate a human organ; it just needs to accurately answer a question that researchers are using it to address.

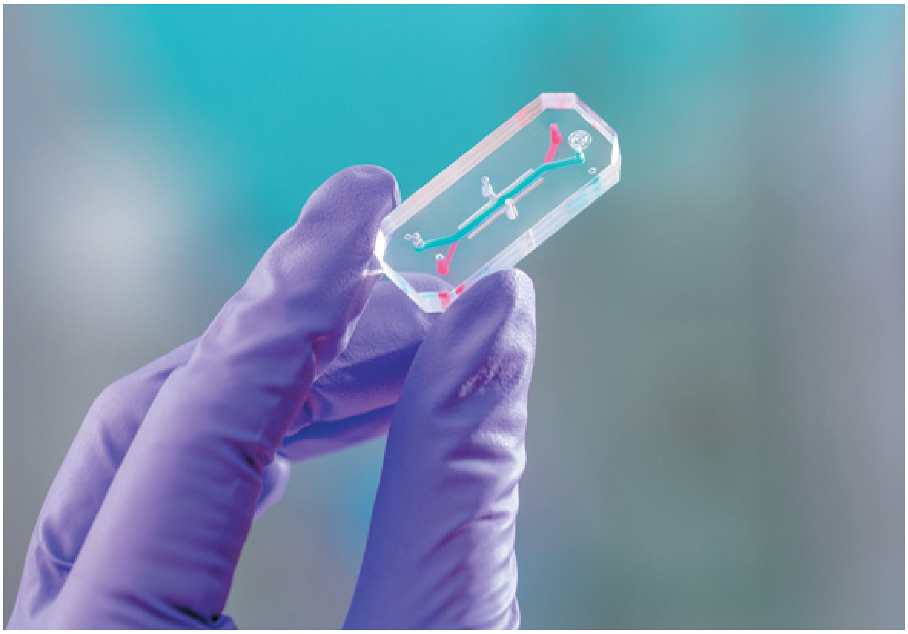
Emulate's liver chip is the company's most popular organ model. That's because one of the primary reasons new drugs fail is that animal models don't reveal human hepatotoxicity—a condition that occurs when the liver is damaged by exposure to harmful substances. In a study published in 2022 in *Communications Medicine,* an Emulate-led team evaluated 870 liver chips across a blinded set of 27 known hepatotoxic and nontoxic drugs. The chips correctly identified 87 percent of hepatotoxic drugs—none of which were detected with animal models. Further, the chips did not inaccurately label any safe drugs as toxic, as animal models commonly do. Based on these findings, the authors calculated that the pharmaceutical industry could generate an additional $3 billion or more a year if it routinely used liver chips.

Increasing so-called predictive capability saves time, money and animal lives, according to a 2022 case study by Moderna. The pharmaceutical company used Emulate's liver chips to screen 35 drug-delivery molecule candidates. The liver chips allowed it to complete that task in a year and a half at a cost of $325,000. If the company had performed the same tests in nonhuman primates, Moderna says, it would have cost more than $5 million and taken five years.

Academic labs are also inventing new tools. Vasiliki Machairaki, a molecular biologist at the Johns Hopkins School of Medicine, has been creating a nonanimal model of Alzheimer's disease, inspired by her grandmother's diagnosis. Machairaki uses blood samples collected from people with Alzheimer's to make stem cells, which she differentiates into brain cells and brain organoids, self-assembled three-dimensional tissue cultures that look a bit like trays of pale Dippin' Dots. The organoids begin to show signs of their donors' pathology within about four months, enabling the researchers to test the effectiveness of various pharmaceuticals against Alzheimer's. "This is a personalized model that could eventually tell you the best drugs to use for different patients," Machairaki says.

In a Johns Hopkins lab headed by biomedical engineer Deok-Ho Kim, researchers culture human heart tissue across plates holding 24 dime-size wells. Electrodes stimulate the heart tissue with an electric current, and magnetic sensors allow the researchers to measure the twitching force of the beating muscle. Some lab members are testing the cardiotoxicity and effectiveness of new chemotherapy drugs—many of which fail in humans because they are unsafe or don't work—and others are screening new therapies for muscular dystrophy, a group of wasting diseases. Treatments have been found to improve symptoms of some forms of the disease in mouse models, but they don't work in human patients, many of whom die from heart failure in their 30s.

The engineered heart models, like the brain organoids, are derived from stem cells that carry the genes of their donors. This opens up opportunities for studying patients who have been traditionally overlooked in research, including ones with rare diseases for which "no [animal] model exists at all," Tagle says. "Rare diseases



Advances in so-called organ chips could accelerate the phasing out of animal testing in laboratories—and lead to better results.

are poorly studied, and there's little interest in developing animal models for them because it takes a lot of time and effort."

Molecular biologist Anicca Harriot says the ability "to do experiments that are directly relevant to the patient" was a motivating factor in her decision to join Kim's lab as a postdoctoral fellow. Harriot was diagnosed with a rare blood-clotting disorder when she was a child, and doctors couldn't tell her anything about her prognosis, because the small number of patients with her condition had precluded clinical trials. Conducting research with human stem cells rather than animal models "helps to shift this work toward equity," she says.

Conferences dedicated to exploring alternatives to animal-dependent methods, such as the Microphysiological Systems World Summit, attract 1,000 or more attendees. Many of them are doctoral students and postdocs who are looking to build a scientific career using what they see as the tools of the future.

IN NOVEMBER 2022 U.S. federal prosecutors unsealed an unusual indictment: felony charges against eight people for allegedly running an international monkey-trafficking ring. Until 2020 China was the world's largest supplier of captive-bred lab monkeys. But wildlife trade bans during the COVID pandemic triggered an international shortage in lab monkeys—around 70,000 of which are used every year in the U.S. alone. According to the government, the trafficking group had used false documents to smuggle hundreds of illegally captured wild long-tailed macaques—an endangered species—from Cambodia to Florida and Texas to supply the research industry.

Locke sees this "hot mess" as something that should have been a glaring message to the scientific community about the need to be more proactive in its pivot away from lab animals and toward human-centric alternatives. By and large, though, that wasn't the reaction. Instead "the research community screams, 'We need more macaques!'" Locke says—a shortsightedness that he equates to "asking in the 1950s, 'How do we get more slide rules?'"

The cultural shift away from animals has not been easy. "To say you want to have a research career but don't want to do animal work, you're still a little bit laughed at," says Antonia Egert, a physician at the University Medical Center Freiburg in Germany.

On top of that, it's difficult for researchers to make the transition because regulators have yet to clearly spell out what is needed for an alternative model to replace an existing animal-based test, says Breanne Kincaid, a doctoral student in environmental engineering at Johns Hopkins. Although the FDA and EPA broadly state that they will accept nonanimal toxicity data, their regulators have not "put pen to paper to say these are the accepted standards you need to meet to use your model," she continues. This means scientists who use alternative methods have no guarantee that findings they submit to regulators "won't simply be met with a vote of no confidence and a request for additional animal data."

Policymakers have also sent mixed signals about whether labs should be investing in alternative methods. When President Biden signed the FDA Modernization Act 2.0 in 2022, the new law did away with a 1938 mandate that animal testing be a part of every new drug application and authorized the use of the best nonclinical model instead. The Modernization Act is "a really encouraging sign of change," Locke says, but it has yet to filter down to specific guidelines, standards or policies.

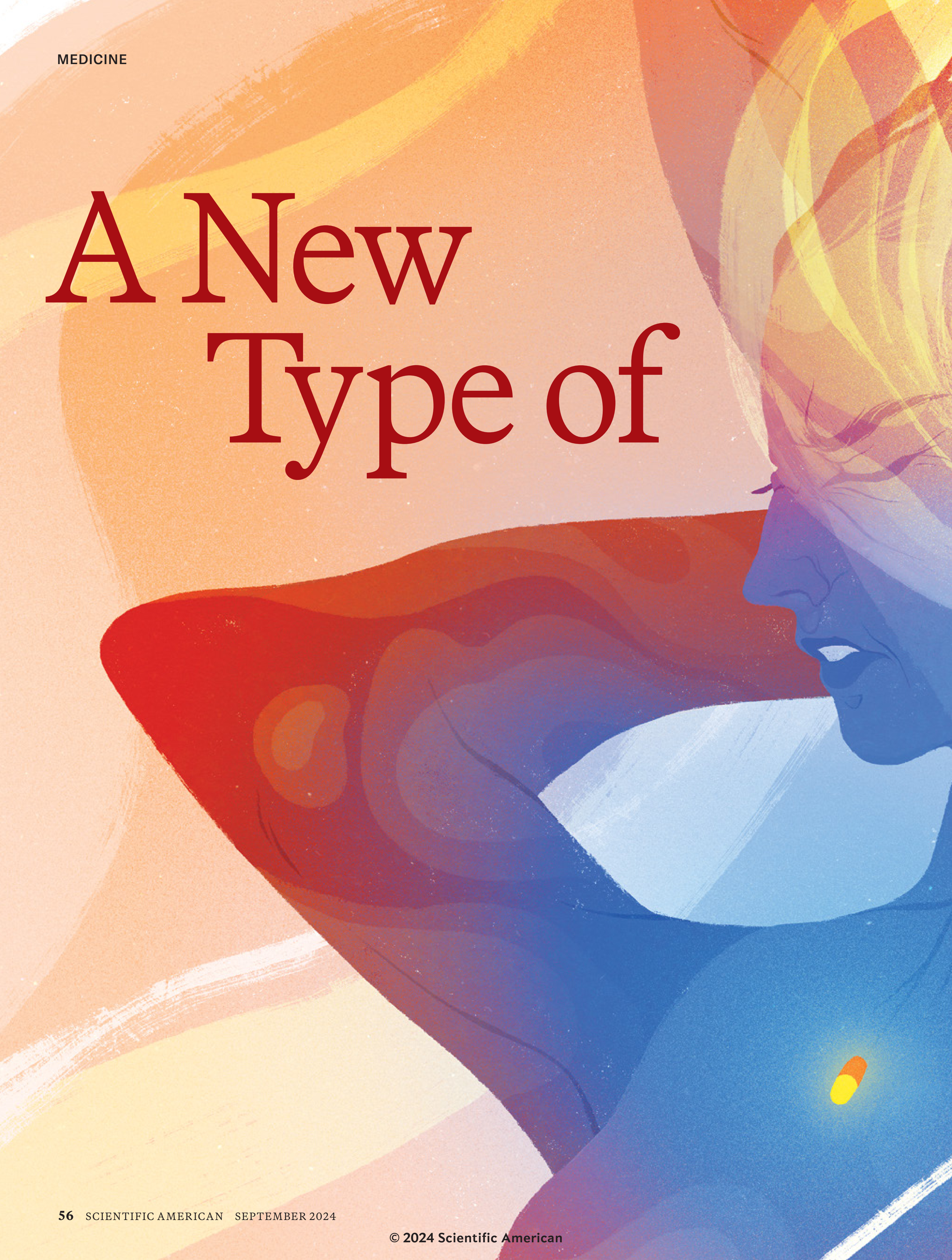
In response to questions about the agency's plans for translating the Modernization Act to real-world decision-making, an FDA spokesperson wrote, "While the FDA is committed to doing all that it can to reduce the reliance on animal-based studies in the broad context of human drug development, animal testing is scientifically necessary in most circumstances because the current state of science does not support replacing all animal studies with alternative methods."

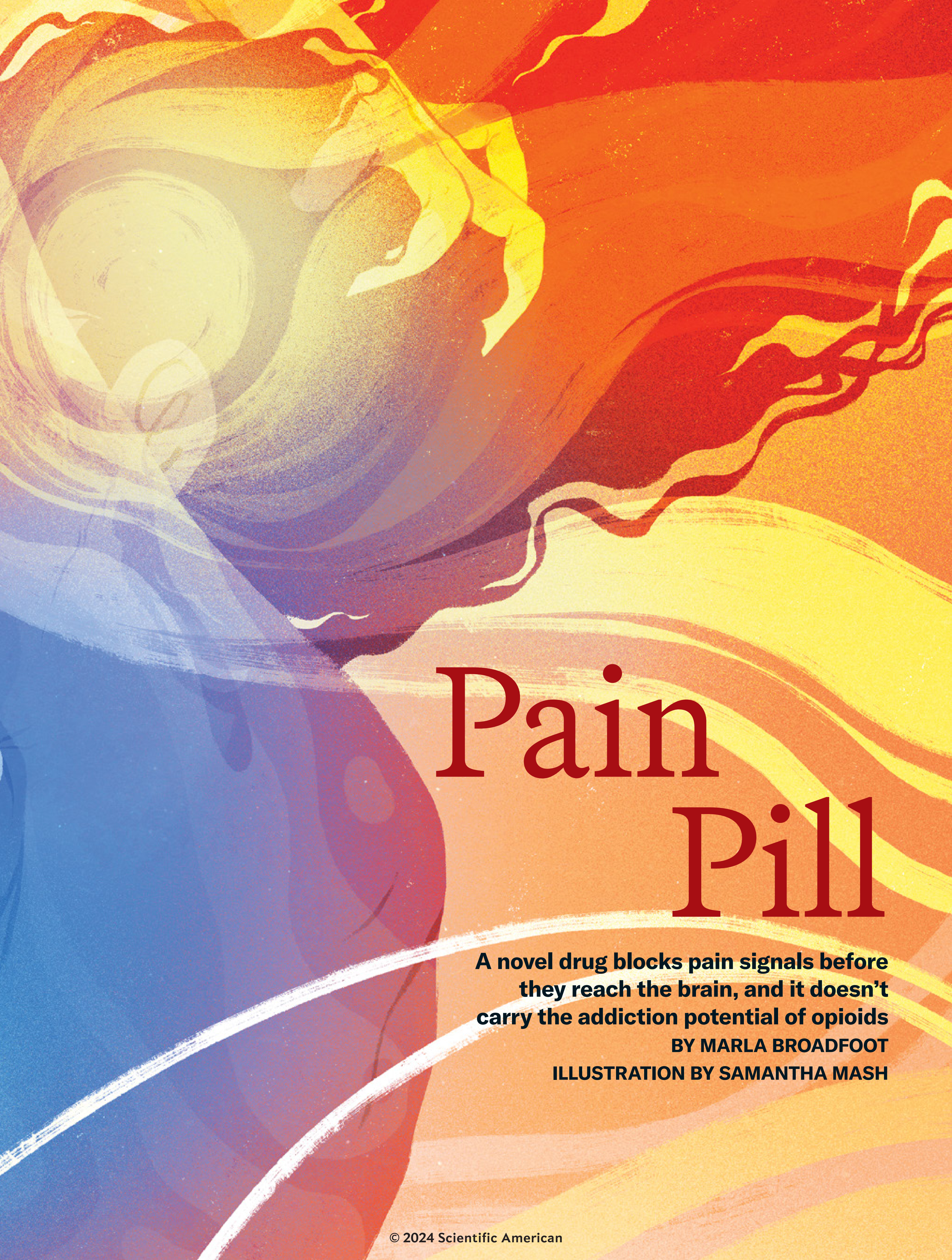
That stance could change if the FDA Modernization Act 3.0, introduced by legislators in February 2024, is passed. It would require the FDA to establish a process for qualifying new methodologies so they can be used for drug development. This year the NIH distributed upward of $30 million to several academic centers that will work with input from the FDA over the next five years to qualify some organ and tissue chips as sanctioned drug-development tools. If the bill passes, "I'd anticipate a surge in demand for these things, largely coming from the pharmaceutical industry," Tagle says.

Tagle and his colleagues recently secured around $300 million from the NIH Common Fund for a 10-year project to develop and validate new methods for biomedical research. The Complement Animal Research in Experimentation program will encourage interdisciplinary teams that include engineers, computational scientists and physicists to advance scientific development and regulatory acceptance of nonanimal methods. Reaching the next generation of scientists through workshops and conferences is another integral part of the plan, Tagle says, "so that when they start their own labs, it becomes natural for them to employ those new technologies." ●

MEDICINE

A New Type of





Pain Pill

A novel drug blocks pain signals before they reach the brain, and it doesn't carry the addiction potential of opioids

BY MARLA BROADFOOT

ILLUSTRATION BY SAMANTHA MASH

WHEN DOCTORS ASK SARA GEHRIG to describe her pain, she often says it is indescribable. Stabbing, burning, aching—those words frequently fail to depict sensations that have persisted for so long they are now a part of her, like her bones and skin. "My pain is like an extra limb that comes along with me every day."

Gehrig, a former yoga instructor and personal trainer who lives in Wisconsin, is 44 years old. At the age of 17 she discovered she had spinal stenosis, a narrowing of the spinal cord that puts pressure on the nerves there. She experienced bursts of excruciating pain in her back and buttocks and running down her legs. That pain has spread over the years, despite attempts to fend it off with physical therapy, anti-inflammatory injections and multiple surgeries. Over-the-counter medications such as ibuprofen (Advil) provide little relief. And she is allergic to the most potent painkillers—prescription opioids—which can induce violent vomiting.

Today her agony typically hovers at a 7 out of 10 on the standard numerical scale used to rate pain, where 0 is no pain and 10 is the most severe imaginable. Occasionally her pain flares to a 9 or 10. At one point, before her doctor convinced her to take antidepressants, Gehrig struggled with thoughts of suicide. "For many with chronic pain, it's always in their back pocket," she says. "It's not that we want to die. We want the pain to go away."

Gehrig says she would be willing to try another type of painkiller, but only if she knew it was safe. She keeps up with the latest research, so she was interested to hear earlier this year that Vertex Pharmaceuticals was testing a new drug that works differently than opioids and other pain medications.

That drug, a pill called VX-548, blocks pain signals before they can reach the brain. It gums up sodium channels in peripheral nerve cells, and obstructed channels make it hard for those cells to transmit pain sensations. Because the drug acts only on the peripheral nerves, it does not carry the potential for addiction associated with opioids—oxycodone (OxyContin) and similar drugs exert their effects on the brain and spinal cord and thus can trigger the brain's reward centers and an addiction cycle.

In January Vertex announced promising results of clinical trials of VX-548, which it is calling suzetrigine, showing that it dampened acute pain levels by about one half on that 0-to-10 scale. The company is applying for U.S. Food and Drug Administration approval for the drug this year.

Other pain drugs that target sodium channels are

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now being developed, some by firms motivated by Vertex's success. Navega Therapeutics, led by biomedical engineer Ana Moreno, is even using molecular-editing tools such as CRISPR to suppress genes involved in chronic pain. "We are definitely hopeful that we can replace opioids, and that's the goal here," she says.

One in five U.S. adults—51.6 million people as of 2021—is living with chronic pain. New cases arise more often than other common conditions, such as diabetes, depression and high blood pressure. Yet pain treatments have not kept pace with the need. There are over-the-counter pills such as aspirin, acetaminophen (Tylenol) and nonsteroidal anti-inflammatories (NSAIDs) such as Advil. And there are opioids. The glaring inadequacy of existing medications to alleviate human suffering has fueled the ongoing opioid epidemic, which has led to more than 730,000 overdose deaths since its start.

VX-548 does have limits. It left some patients in significant discomfort, and so far it has been tested mostly in those with acute pain, not the much larger problem of chronic pain. Gehrig says she wants more assurances that the drug won't cause nasty side effects before she takes it.

But the compound has shown that a new mechanism of pain relief is possible, says Stephen Waxman, a neurologist at Yale University who studies pain signals—and who is not involved in the Vertex clinical trials. Future drugs using that mechanism are likely to be even more effective, he notes. Waxman used to tell patients that a new means of managing their pain was on the way but that it may not happen for many years. "Now I can relax the caveat and say I think things are going to happen fairly quickly," he says.

THE PAIN MEDICATIONS that exist today are, in large part, derivatives of natural products that have been around for thousands of years. Aspirin originally came from willow bark. Morphine and codeine were derived from the opium poppy plant. Prescriptions for what evolved into the two major classes of pain drugs—NSAIDs and opioids—were etched on clay tablets by ancient Sumerians 4,000 years ago.

Modern research on the molecular mechanisms underlying pain, conducted during the past two decades, makes a different approach possible. Scientists know that our body is home to large numbers of pain-signaling nerve cells that innervate our skin, muscle and visceral tissues. These cells act like an alarm system, detecting threatening stimuli such as extreme temperatures, sharp objects or noxious chemicals. In response to these cues, they create impulses that carry pain signals along nerve fibers to clusters of cells known as dorsal root ganglia, which are tucked beside the spinal cord. From there, the signals continue their journey upward to the brain, where pain becomes reality. "This is the axis of pain,"

A young Pakistani firewalker had a genetic mutation affecting pain-signaling neurons, letting the boy walk on burning coals without feeling pain.

says Rajesh Khanna, a pharmacologist and pain researcher at the University of Florida.

Central to this pathway are sodium channels, cellular gates scattered throughout the membranes of nerve cells. Whenever there is a shift in membrane potential, these gates open to allow the influx of sodium ions that generate the electric currents responsible for nerve impulses. Normally those pain signals serve a protective purpose—alerting someone to pull their hand away from a hot stove or noting inflammation or injury that needs to be addressed. But in chronic pain, those protective mechanisms can go awry.

A voltage-gated sodium channel (or Na_V, Na standing for sodium and V for voltage) seems like the ideal target for treating pain; after all, if you can stop it, you can stop pain signals from being transmitted. Yet because these channels control electrical impulses that power the heart and brain, blocking them willy-nilly would impair vital functions. That's why novocaine and lidocaine—which are sodium-channel blockers—are used as local numbing agents but can cause serious side effects if administered systemically. So scientists trying to block these pain pathways searched for channels that act more often in the peripheral sensory nerves, eventually identifying three: $Na_V1.7$, $Na_V1.8$ and $Na_V1.9$.

$Na_V1.7$ and $Na_V1.8$ are the pivotal players in pain signaling. "They work in tandem, like dominoes," Waxman says. "$Na_V1.7$ initiates the electrical signal, and $Na_V1.8$ takes off, producing 80 percent of the current underlying the action potential." ($Na_V1.9$ plays a more niche role in setting the pain-signaling neurons' threshold potential.)

Beginning about 20 years ago, a series of reports linked these channels to pain disorders in humans. A mutation in the *SCN9A* gene, which encodes $Na_V1.7$, was discovered in a family in China who suffered from a rare condition called erythromelalgia, or "man on fire" syndrome. In people with this condition, mild warmth can trigger attacks of searing pain that feels like a blowtorch. Waxman found that mutations in patients with erythromelalgia made the $Na_V1.7$ channel overactive, causing pain-signaling neurons "to scream when they should be whispering." Elsewhere, researchers found a mutation with the opposite effect in a young Pakistani firewalker. That mutation extinguished the flow of pain-signaling ions through the $Na_V1.7$ channel. As a result, the boy could walk on burning coals without feeling pain.

The discovery of the genetic basis of his condition—known as congenital insensitivity to pain—set off a race in the pharmaceutical industry to identify molecules that could block $Na_V1.7$. The goal was to provide a similar pain-free existence to the rest of the population. "This was the holy grail. You have a protein, you mutate it, you have no pain—it's got to be the target," Khanna says. "A lot of pharma companies put a lot of money into this effort, but none of those compounds have been successful."

Many compounds targeting $Na_V1.7$ looked promising in the laboratory, only to fail in clinical trials. Pharma companies AstraZeneca and Genentech both developed candidates that stalled after phase 1 trials. Pfizer's PF-05089771 failed to perform in a battery of tests evoking pain in healthy volunteers. Biogen scrapped development of its $Na_V1.7$ inhibitor, vixotrigine, after lackluster results from a string of phase 2 trials in several types of neuropathic pain. After more than a decade of false starts, investment dwindled, and drug candidates disappeared from development pipelines.

In 2017 the White House declared a public health emergency for the opioid crisis, which was killing 91 people every day. That same year Francis Collins, then director of the National Institutes of Health, gathered industry leaders as well as basic scientists and clinicians to discuss strategies to combat the crisis. Sean Harper, who led R&D at biopharmaceutical giant Amgen at the time, remembers the meeting had representatives from about 20 of the world's top pharma companies, and Collins asked what they had in the works. "It was sad," Harper recalled. "There were very few companies that were working on anything other than tamper-proof, crush-proof opioid pills."

Across the industry, novel pain-drug research stagnated. Amgen, which had identified a number of potential $Na_V1.7$ inhibitors, eventually shuttered not only its pain research but also the bulk of its neuroscience program. In general, "I think what happened is people sort of felt that it was just too hard," Harper says.

One big reason for the difficulty had to do with the nature of the targets themselves. The Na_V channel family contains nine closely related members that share more than 50 percent of their genetic sequence. Because of this similarity, the sodium channel inhibitors developed in the 2000s were often unable to target one subtype without hitting others. "The selectivity was terrible, frankly," says John Mulcahy, a chemist and CEO of the San Francisco–based biotech firm SiteOne Therapeutics. "It's taken a long time to overcome that."

> "For many with chronic pain, it's always in their back pocket. It's not that we want to die. We want the pain to go away."
> —Sara Gehrig *pain patient*

AT VERTEX, RESEARCHERS BELIEVED that the compounds that had been tested before were simply not selective enough or didn't attach to a channel for enough time and that to find molecules that worked they just needed to keep searching. To speed up their hunt, they had been working on a technology that could measure the effect of massive numbers of molecules, at various concentrations, on the opening and closing of several types of sodium channels. Traditionally, researchers have studied sodium channels using a laborious method called patch-clamp electrophysiology. The technique involves isolating part of a cell's membrane, applying voltage to trigger its channels to open, adding one single potential drug, and then recording the oscillating waves of electrical activity.

In the early 2000s Vertex scientists Jesús González and Michael Maher designed a system called E-VIPR (for electrical stimulation voltage ion probe reader) to test many compounds against one channel very quickly. The system uses a high-density array of cells, each of which expresses one type of sodium channel. Tiny electrodes generate an electrical field that can stimulate the channels as many as 100 times per second. As these channels open, a voltage-sensitive dye shifts from orange to blue, and the color change is captured by a sophisticated optical detection tool.

"It's a very quick process, faster than the human eye can detect, but incredibly rich in information," says Paul Negulescu, Vertex's senior vice president of research and head of its pain program. The engineering group developed the first generation of the technology about two decades ago, and it is on the third generation now. "That's been the workhorse. And we have tested tens of thousands of compounds on the system that runs every day," he adds.

With this method Vertex could extensively test how a potential drug interacts with a particular channel. Sodium channels undergo big shape changes as they open and close, with pieces of the protein moving up and down with dizzying speed. "It's kind of like a bucking bronco," Negulescu says. "The drug has to get on the bucking bronco and stay on while it's going through its paces and eventually settle that bucking bronco down so it stops moving." A drug candidate might land on the channel for a time, only to get kicked off once its gyrations prove too much. Or it might hop onto another channel, generating unwanted off-target effects.

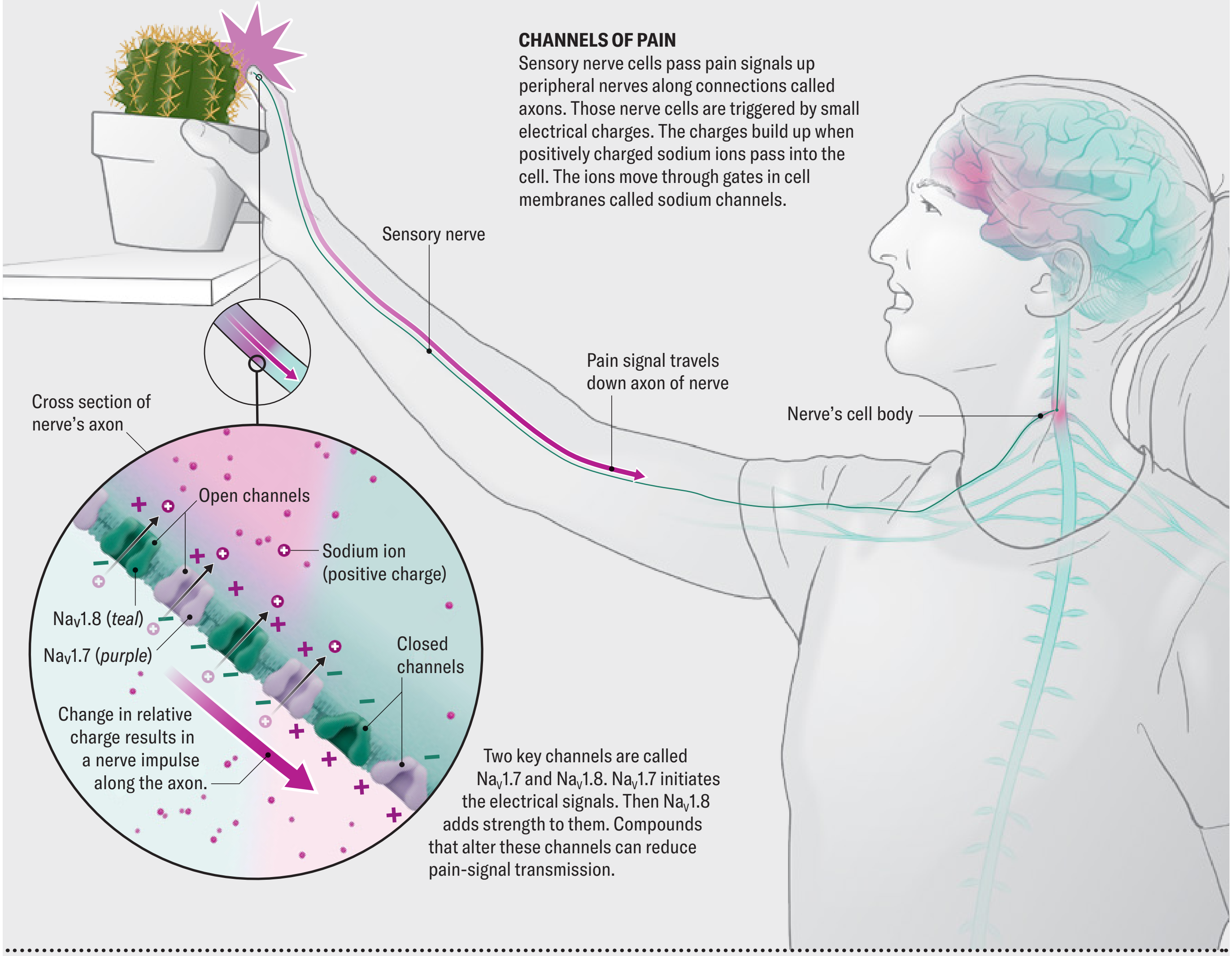
Negulescu says that Vertex's approach tries to mimic the physiological states of the sodium channel, putting it through multiple cycles of opening and closing to make sure that any promising new

Relieving the Agony of Pain

Pain is “felt” in the brain, but pain signals usually start in peripheral nerves in the body. Opioid medications, such as OxyContin, can affect the brain end of the path, blunting pain but also leading to addiction. New types of drugs, however, focus on nerve cells in the periphery, dampening the pain signals where they start.

CHANNELS OF PAIN

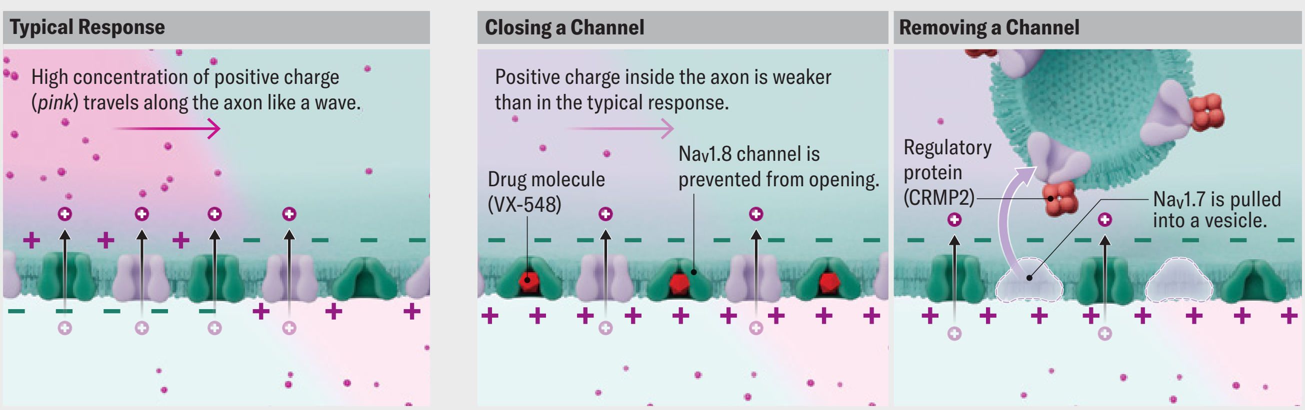
Sensory nerve cells pass pain signals up peripheral nerves along connections called axons. Those nerve cells are triggered by small electrical charges. The charges build up when positively charged sodium ions pass into the cell. The ions move through gates in cell membranes called sodium channels.



Two key channels are called Na_V1.7 and Na_V1.8. Na_V1.7 initiates the electrical signals. Then Na_V1.8 adds strength to them. Compounds that alter these channels can reduce pain-signal transmission.

TWO CHANNELS, TWO WAYS FOR RELIEF

Typically open sodium channels let a lot of positively charged ions into the cell. The channels constantly shift between open and closed positions. A new drug called VX-548 binds Na_V1.8 channels in their closed position, reducing the number of sodium ions crossing into cells. Vertex, the drugmaker, conducted clinical trials showing this action reduces pain. Another firm, Regulonix, is targeting Na_V1.7 channels. Their compound affects a protein that regulates Na_V1.7. Hindering that protein means many of the channels are pulled out of the cell membrane, weakening the pain-related signal.



Graphic by Falconieri Visuals

drug stays put. "Most of the methods don't do it that way," he says. "And because of that, I believe we end up with pharmacology that isn't translating when we get to people." The company used its proprietary method to generate data on a variety of different sodium channels. As the industry continued to focus on $Na_V1.7$, Vertex started to see success with $Na_V1.8$ and pushed forward a program on the neglected channel. "I think we zigged when others zagged," Negulescu says.

Vertex launched its first clinical trials of a $Na_V1.8$ inhibitor in 2015. It wasn't effective enough, and neither were the two immediately following it. But finally one was tolerated well by a small group of patients and relieved some of their pain. That was VX-548, and it prompted the company to move ahead with bigger studies in 2022.

Two years later, in January 2024, Vertex announced positive results of two large, pivotal clinical trials. The researchers enrolled about 1,100 people, each of whom was undergoing bunion removal or tummy tuck surgery, operations commonly used to model acute pain. Study participants got a placebo, VX-548 or the drug combo of hydrocodone (an opioid) and acetaminophen, known as Vicodin.

When measuring pain relief on the 0-to-10 pain scale, the new drug performed just as well as Vicodin without the addiction risk. Both treatments reduced pain by about three points, from about a 7 to a 4. And in the people recovering from abdominal surgery, relief kicked in more quickly than it did for those who got Vicodin.

The drug provided less relief than Vicodin for bunionectomy patients when using a different pain scale. Still, those taking VX-548 reported fewer side effects—such as nausea, constipation, headache and dizziness—than those on the placebo, indicating the treatment was generally safe. (Untreated pain in the placebo group could increase side effects because it can elevate stress levels, upsetting digestion or triggering headaches.)

Studies suggest that even a 3-point drop in pain can have a meaningful impact on quality of life. Gehrig, the Wisconsin patient, remembers a time when her pain level registered at a 4, and she was able to work. After a botched surgery sent her pain skyrocketing, she was forced to go on disability.

If approved, VX-548 could help people such as Gehrig by offering relief that lands somewhere in between drugs such as acetaminophen, which are safe but limited in their power, and stronger opioids, which come with serious risks. It could provide relief to patients who are allergic to or simply cannot tolerate the other drugs. Moreover, it could open up options for individuals who want to avoid the risks of drug dependency.

Vertex is applying for FDA approval of the drug for cases of moderate-to-severe acute pain. Many experts agree that while it makes sense experimentally to go after acute pain first, the bigger need is providing relief to people whose daily life is disrupted by chronic pain. Vertex scientists think the drug will work for that type of agony because the mechanisms underpinning chronic and acute pain are similar. It reported positive results from a smaller efficacy and safety trial of VX-548 in diabetic peripheral neuropathy, a common type of chronic pain caused by nerve damage from high blood glucose, and plans to move forward with a phase 3 trial.

In addition, the company launched a separate study testing the drug in a form of chronic lower back pain known as lumbosacral radiculopathy. And Vertex researchers continue to use their drug-discovery platform to evolve compounds that are more potent and more selective. "We are all about serial innovation," Negulescu says. The company already has a next-generation $Na_V1.8$ inhibitor, VX-993, in clinical trials.

OTHERS IN THE PAIN FIELD have been watching Vertex closely and are excited by its latest results. "I think the great contribution that Vertex has made here generating the clinical data that they have with their program is to make people understand that, hey, this is not a hopeless thing," Harper says. He, with other investors, launched a company called Latigo Biotherapeutics to develop sodium channel inhibitors.

Waxman says the Vertex findings were modest yet important—so important that he called VX-548 "a game changer," not because it will change clinical practice on its own but because it will transform the research pipeline. "This is going to be like the development of the statin drugs," he says. "The first statin drugs were, in retrospect, not very good. But they set the stage and really were the impetus, and the ones we have now are life-changing."

Only a handful of companies are openly developing pain therapeutics going after $Na_V1.8$ or $Na_V1.7$, which remains a viable target. More may be working in "stealth" (Merck's patent activity indicates it is dabbling in the field), and others most likely will join the effort, emboldened by Vertex's progress. Some are already designing small molecules to block the sodium channels or nearby proteins; some are modifying natural toxins to disable the transmission of pain signals; still others are using gene therapy to turn down the signal at its source.

Latigo, Harper's start-up, is the latest to emerge in this space. In February 2024 the California-based biotech launched with $135 million in funding and a $Na_V1.8$ inhibitor, LTG-001, in phase 1 clinical trials. Early on, the company pursued both $Na_V1.7$ and $Na_V1.8$. But Harper says when it saw that one of Vertex's drug candidates had achieved positive results in both acute and chronic pain models, that "helped to push $Na_V1.8$ to the front of the queue." Now Latigo has a few other small molecules it is getting ready to test. Harper says that typically when a company has taken an entirely new class of medicines into the clinic, as Vertex has, there are many others "nipping at their heels."

Previously, Harper says, the historical lack of investment in pain medicine made for "pretty light competition." According to an analysis by BIO, a biotech industry trade group, investment in pain and addiction drug development is remarkably low given the societal burden of these diseases. In 2021 pain and addiction companies raised $228 million in venture capital. That represented only 1.3 percent of total therapeutic venture funding in the U.S. In contrast, oncology companies brought in $9.7 billion, or 38.3 percent of the venture funding pie. What's more, most industry pain programs have focused on different formulations of opioid drugs rather than riskier forays into new mechanisms.

Michael Oshinsky, director of the Office of Preclinical Pain Research at the National Institute of Neurological Disorders and Stroke, says a leading reason for pharma's persistent focus on opioids and neglect of other research avenues is that opioids have been a safer bet. "There's a 30 percent chance to have a clinical trial for an opioid making it to the market. That's really crazy high for therapeutics development. And it's about a 0.7 percent chance for something that doesn't hit the opioid receptor," he says.

Oshinsky co-chairs the NIH's Helping to End Addiction Long-term (HEAL) initiative, which aims to accelerate research on new nonaddictive pain meds. "What we do is we try to de-risk targets," he says. The program has been helping up-and-coming developers of sodium channel inhibitors such as Regulonix, SiteOne and Navega by validating their targets, optimizing their compounds or testing their approaches in preclinical models.

University of Arizona spin-off Regulonix is sticking with $Na_V1.7$ as a target but is going after it differently than its predecessors. Rather than blocking the sodium channel, the company is trying to remove $Na_V1.7$ from the cell membrane. Without the channel there will be fewer sodium ions that can cross into the cell. University of Florida's Khanna, who co-founded Regulonix and is chief scientific officer of the company, says an early version of its compound successfully affected $Na_V1.7$ signaling in rat, mouse and pig models of acute and chronic pain. But, he admits, "we're nowhere close to being in humans."

A different approach is to take naturally occurring sodium channel blockers—such as the tetrodotoxin that makes puffer fish so lethal—and modify them to block channels predominantly found in pain-sensing neurons. SiteOne, started by Stanford University scientists, is following this game plan. In 2022 it began a collaboration with Vertex to develop its therapeutic candidates that target $Na_V1.7$. The company has also secured additional nih funding to work on a $Na_V1.8$ inhibitor called STC-004. "In our experience, $Na_V1.7$ inhibitors can act almost like an on-off switch for pain," Mulcahy says. A $Na_V1.8$ drug "is a little bit different—it's more like a dimmer switch."

When measuring pain relief on a 0-to-10 pain scale, the new drug performed just as well as Vicodin but without the addiction risk.

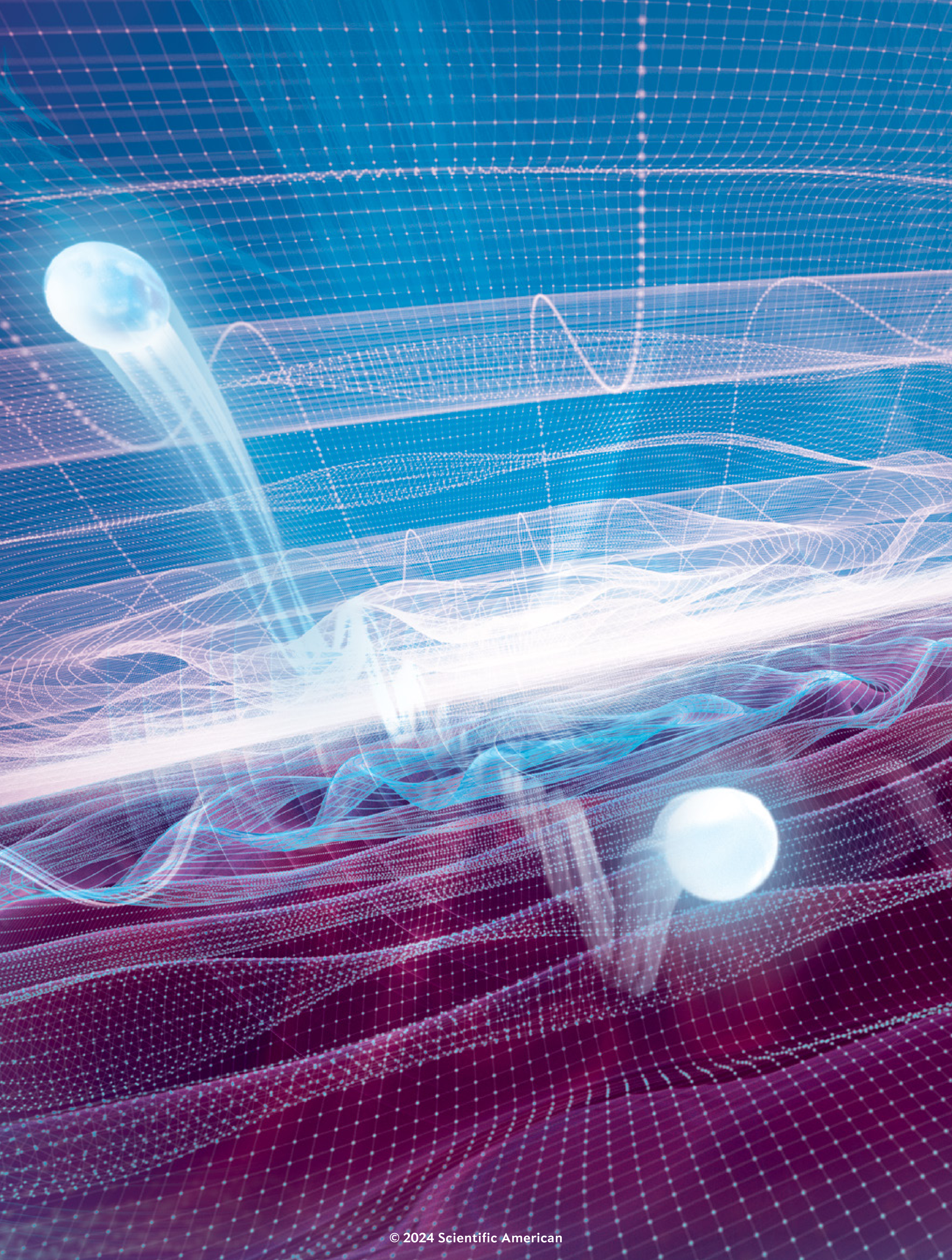
Finally, instead of manipulating existing pain channels, some researchers are trying to keep so many of them from forming by reducing the activity of genes that encode them. That type of gene therapy is being pursued by Moreno and her company Navega. They are working with a technology that Moreno developed during her doctoral research at the University of California, San Diego. There she used CRISPR and its older gene-editing counterpart, zinc finger proteins, to target genes that help to build $Na_V1.7$; the result was to suppress or even prevent pain in rodents. Since launching Navega, she and her team have shown that the approach works for various kinds of pain—including neuropathic, chemotherapy-induced, inflammatory, visceral and arthritic—and they are quickly advancing toward first-in-human trials.

"Because we have long-lasting results, we're going to focus on intractable pain," Moreno says. Navega plans to test the gene therapy in that rare subset of patients with "man on fire" syndrome, who have known mutations causing their pain, before thinking about larger, more complicated clinical trials for chronic pain. "We get e-mails all the time from patients who are suffering from all over the world," she says. "It's very motivating."

FOR GEHRIG, THE PROSPECT of adding a new and effective type of pain reliever to her medicine cabinet has given her hope. But she has tried new things before, only to be brought down by debilitating side effects. Gehrig says she will wait to try VX-548 until her doctor can assure her it is safe. The trials showing few side effects are important, she says, but she'd prefer that the drug be in clinical use for a while before she takes it herself.

For now she relies on other ways to cope with her pain. She runs six support groups for the U.S. Pain Foundation, including one for the LGBTQ community and another for people based in Wisconsin. After years of trying everything else, she has experienced the most healing from a daily practice of reflection and prayer, mindfulness and meditation. "It's a constant listening to my body every day, really trying to learn self-love and self-compassion—that's been my medicine," she says. Her self-healing practices keep her going. But she wouldn't mind a little more help from the medical world. ●

FROM OUR ARCHIVES
Unbound from Opioids. Claudia Wallis; January 2020. ScientificAmerican.com/archive



Quantum Spacetime

PHYSICS

Proposed experiments would search for signs that space and time obey quantum rules

BY NICK HUGGETT AND CARLO ROVELLI

ILLUSTRATION BY MARK ROSS

THERE IS A GLARING GAP in our knowledge of the physical world: none of our well-established theories describe gravity's quantum nature. Yet physicists expect that this quantum nature is essential for explaining extreme situations such as the very early universe and the deep interior of black holes. The need to understand it is called the problem of "quantum gravity."

The established classical concept of gravity is Einstein's general theory of relativity. This spectacularly successful theory has correctly predicted phenomena from the bending of light and the orbit of Mercury to black holes and gravitational waves. It teaches us that the geometry of space and time—spacetime—is determined by gravity. So when we talk about the quantum behavior of gravity, we're really talking about the quantum behavior of spacetime.

We don't currently have an established theory of quantum gravity, but we do have some tentative theories. Among them, loop quantum gravity (which one of us, Rovelli, helped to develop) and string theory are two leading contenders. The former predicts that the fabric of spacetime is woven from a network of tiny loops, whereas the latter posits that particles are fundamentally vibrating strings.

Testing these theories is difficult because we can't study the early universe or black hole interiors in a laboratory. Physicists have mostly assumed that experiments that could directly tell us something about quantum gravity require technology that is many years away.

This situation might be changing. Recent developments suggest it may be possible to perform laboratory experiments that will reveal something about the quantum behavior of gravity. This potential is extremely exciting, and it has raised real enthusiasm among theoretical and experimental physicists, who are actively trying to develop the means to carry out the investigations. The proposed experiments could test the predictions of quantum gravity theories and provide support for the assumptions they're based on.

The experiments all involve events happening at low energies, where the predictions of strings, loops, and the like agree, so they aren't going to tell us which specific theory of quantum gravity is correct. Still, experimental evidence that gravity is actually quantized would be groundbreaking.

We already have plenty of observations about gravity's effects on the quantum behavior of matter. Albert Einstein's theory works fine in these situations, from stellar dynamics, to the cosmological formation of galaxy clusters, all the way to laboratory experiments on the effect of Earth's gravity on quantum systems. But in all these scenarios, gravity itself behaves in a way that is consistent with classical physics; its quantum features are irrelevant. What's much more difficult is to observe phenomena in which we expect gravity to behave quantum mechanically.

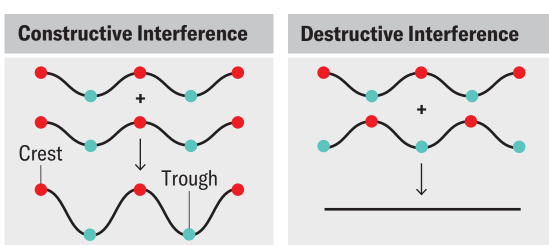
We both have worked on quantum gravity throughout our careers—Rovelli as a physicist and Huggett as a philosopher. We are keenly interested in exploring what these experiments can and cannot tell us about quantum gravity. If they come to fruition, we might be able to see, for the first time, space and time themselves being quantum.

Nick Huggett is a philosopher at the University of Illinois Chicago who specializes in the philosophy of physics.

Carlo Rovelli is a theoretical physicist and writer. He is associated with Aix-Marseille University in France, the University of Western Ontario and the Perimeter Institute in Canada, and the Santa Fe Institute in New Mexico. His latest book is *White Holes* (Riverhead Books, 2023).

THE TWO OF US were discussing the developments recently during a break at a conference. Over coffee in a café in Oxford, England, we came up with a simple thought experiment illustrating how the quantum nature of gravity could be revealed. (Related ideas have been discussed previously by, for instance, Alejandro Perez of Aix-Marseille University in France, in work on dark-matter detection, and Netanel H. Lindner and Asher Peres of the Technion–Israel Institute of Technology.)

Our idea involves "interference," which has been crucial in unraveling many aspects of quantum mechanics. Interference is a phenomenon that applies to waves, quantum or not. All waves have a pattern of crests and troughs; the distance between two crests or troughs is the wavelength. If the crests of two waves meet at a point, they combine to produce a crest twice as high as either alone, and when two troughs meet, you get a trough twice as deep. This kind of interference is said to be constructive. Destructive interference, then, is when a wave and a trough overlap and cancel each other out.

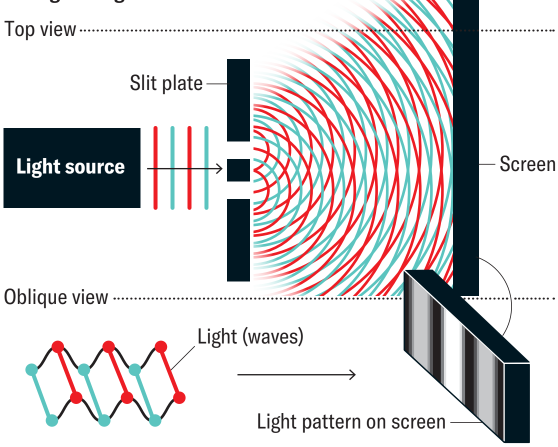


In the 19th century, interference allowed scientist Thomas Young to demonstrate that light acts like a wave. He shined light through two narrow slits to cast an image on a screen behind them. Waves from each slit travel the same distance to reach the point directly between the two slits, so their peaks hit that point at the same time, and they produce constructive interference—that's

Graphics by Jen Christiansen

where Young saw the brightest light. At points farther along the wall to the right of the light source, the wave from the left slit has to travel a slightly longer distance than the wave from the right, so crests and troughs no longer line up, and the height of the added waves decreases. Eventually there is a point at which the wave from the left has to travel half a wavelength farther than the one from the right, and crests line up with troughs to make destructive interference; here Young saw no light. This pattern, known as “Young’s fringes,” repeated along the wall and showed that light is, in fact, a wave.

Young’s Fringes

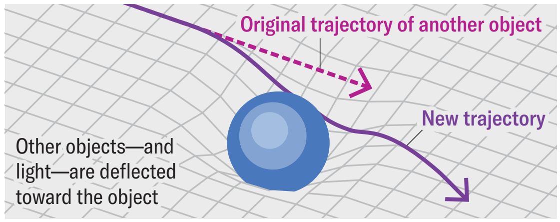


Young’s experiment was purely classical, but variations on this setup became important for quantum physics. In 1923 physicist Louis de Broglie proposed that quantum objects may behave not like little billiard balls, as they had often been thought of, but like waves. If so, particles such as neutrons should also produce a pattern of fringes in a double-slit experiment—and indeed they do, as demonstrated in the 1980s with neutrons produced in a nuclear reactor.

Amazingly, these experiments produce the same results when neutrons pass one at a time through the double slits. Even a single neutron sent through the experiment will create interference, meaning it somehow interferes with *itself.* That can happen only if the neutron acts like two waves that follow two different paths. Because the idea of being in two places at once is so alien to classical particles, a new term was adopted; we say the neutron is in a “superposition” of being both here and there.

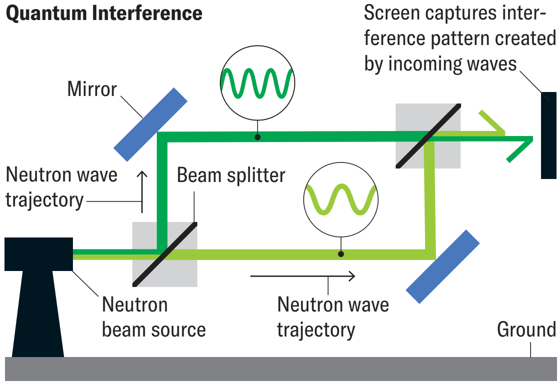
Does this part of quantum weirdness apply to gravity? Does it apply to space and time? To address these questions, we turn to general relativity, which tells us the presence of mass (or energy more generally) means that nearby spacetime will be curved. This curvature, in turn, means that objects will be naturally deflected toward mass, explaining its gravitational attraction. Such spacetime curvature also means that clocks run slower when they are closer to a mass. This effect can be used in an interference experiment that brings quantum mechanics and gravity together—a step toward showing gravity is quantum.

Curving of Space and Time in Response to an Object with Mass



Suppose a neutron, in wave form, is split in two by a mirror that reflects and transmits equal amounts of the wave. The two resulting quantum waves travel different paths to a screen: one travels parallel to the ground and then upward, the other upward and then parallel to the ground, each path forming two sides of a rectangle. The waves are in sync when they leave the mirror, but because of Earth’s gravity, the wave that follows the lower path will oscillate more slowly, and its crests will arrive slightly after those of the wave that follows the higher path. (The effect of the vertical segment is the same on both.) The result is quantum interference caused purely by the curvature of spacetime.

Quantum Interference

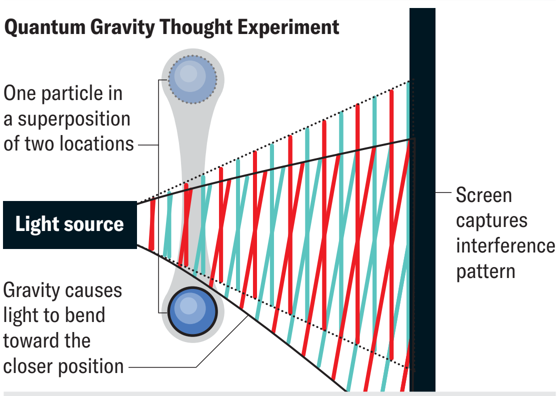


Physicists proposed such an experiment in 1974. The following year Roberto Colella and Albert W. Overhauser, both at Purdue University, collaborated with Samuel A. Werner, then a staff scientist at Ford Motor Company, and successfully carried it out. The team observed the predicted fringe pattern, directly demonstrating the influence of gravity on the quantum behavior of particles, to the great excitement of many scientists. But even though the neutrons in the experiment behaved quantum mechanically, gravity in this case can be described by general relativity, so it is still classical, not quantum.

The breakthrough in the new proposals is that they aim to go further and demonstrate for the first time that gravity, like neutrons and light and all other quantum objects, also has a quantum nature.

ACCORDING TO GENERAL RELATIVITY, all matter, whether a planet, a speck of dust or a neutron, affects spacetime curvature. The deformation of spacetime produced by a small object is minuscule, but it still happens. But what if a small object is in a quantum superposition of locations? Because each position produces a different spacetime geometry, physicists expect that the result is a quantum superposition of geometries. It is as if spacetime has two shapes at once. It is this quantum weirdness of gravity that we hope to one day see in a laboratory.

The simple thought experiment we came up with that day in Oxford shows how it could be done in principle. Imagine that you shine a light past an object in superposition. That light would travel through a superposition of two spacetime geometries. In one geometry it might be far from the object, in which case the effect of gravity would be negligible, and it would travel in a straight line to a screen. In the other geometry it would pass close enough to the object that gravity would have to be taken into account, so it would follow a curved path to the screen. These two different paths mean that when the waves recombine at the screen, they will interfere and produce the telltale fringe pattern.



Crucially, interference will not arise unless gravity can exist in superposition—in other words, unless gravity itself is quantum. If instead gravity is fundamentally classical, no such interference will result. Perhaps, as mathematician and Nobel laureate Roger Penrose has argued, nature picks one of the superposed geometries, causing the mass in superposition to "choose" a single location. Or perhaps there is a single geometry corresponding to a single mass at the average position among its possible locations. Either way, there will be no superposition of geometries, and the light ray will follow a single path and won't be able to interfere with itself. So if interference fringes were to occur in such an experiment, they would, according to standard physics, show quantumlike behavior of gravity such as a superposition of geometries—a momentous result so far not achieved by any experiment.

What are the prospects of carrying out such an experiment? On one hand, the more massive the object we place in superposition, the greater the effect on gravity and hence on the light. On the other, although every object is fundamentally quantum mechanical, most large, everyday things are essentially impossible to observe in superposition because they interact too much with their environments, hiding any interference. We call this effect "decoherence." The larger something is, the more chances it has to interact, and the more it decoheres; scientists who have isolated systems to overcome this effect have won Nobel Prizes.

So we are pulled in two directions for our experiment. We need something big enough to let us see gravitational effects but small enough for us to see its quantum nature. We have to find the sweet spot.

Quantum gravity is characterized by three constants of nature: the speed of light, Isaac Newton's constant describing the strength of gravity, and Planck's constant describing the scale of quantum phenomena. Arithmetically combining them produces a characteristic "Planck mass" of around 20 micrograms (μg). This is about the same mass as that of a flea egg or a strand of hair a few millimeters long: not large but—unlike the energy involved in the big bang—definitely on a human scale. The sweet spot where we hope to search is plausibly around this mass, which involves both gravitational and quantum mechanical constants.

Recently scientists were able to place an object of that mass into a quantum superposition of locations two billionths of a nanometer apart. This separation, however, is still less than a billionth of the distance we'd need for our tests to have a visible effect. The situation may seem hopeless, but to an experimentalist it sounds like a challenge. Labs are working hard to gain better control over the quantum behavior of Planck-mass bodies and to observe the gravitational effects of masses many times lighter than 20 μg.

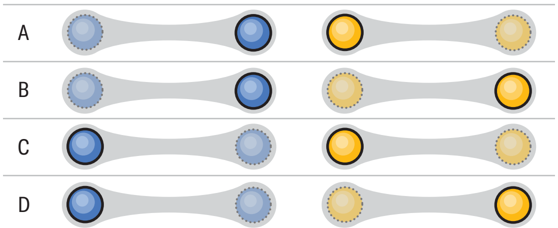
If we want to observe a fringe pattern, though, we can't just shine light at the object in superposition. Even in the gravitational field of a Planck-mass object, the effect will be too small. For us to have any chance of observing what we seek, the light would need a wavelength of 10^{-32} meter—once again in the inaccessible realm found only at the big bang.

WHAT IF, INSTEAD OF LIGHT, we used a second quantum mass to travel near the original mass and exploited *its* quantum wave nature? The heavier the mass, the greater the gravitational force—and the slower it moves, the longer the mass has to experience that force. These two effects are dramatic: fringes should be observable if the two masses are one ten-thousandth of the Planck mass, tantalizingly close to current experimental ability.

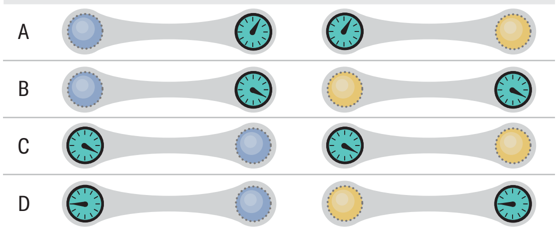
In 2017 a pair of papers about another way of measuring quantum gravity effects in the lab triggered considerable excitement among physicists. The research suggests a strategy for observing a superposition of spacetime geometries that is more subtle and possibly within even closer reach than the one the two of us came up with. Both build on recent advances in theory and experiment that have brought gravity and quantum physics closer together. Both take inspiration from theoretical physicist Richard Feynman's 1957 version of an idea originally proposed by Soviet physicist Matvei Bronstein.

Start with two Planck-mass particles, each in a quantum superposition of locations. Combined, the pair is in a superposition of four possibilities: one where they are close together, two where they are (much) farther apart and one in which they are at the greatest distance from one another in the experiment. Because the geometry of spacetime depends on the distance between the particles, the different possibilities for the particles' arrangement correspond to different geometries. Once again, the particle superposition means that gravity, too, is in a quantum superposition.

Four Configurations of a Pair of Particles in Superposition



According to quantum theory, a stationary quantum particle is a wave that oscillates with a frequency that depends on its energy, so it is a kind of clock. But as we mentioned, gravity affects the rate at which clocks run. In particular, the particles oscillate at different rates in their different arrangements: the closer they are, the slower they oscillate. As a result, the superposed arrangements get out of phase with one another. As before, when waves get out of phase, they experience interference, which in this case can be measured in characteristically quantum correlations between the two particles called "entanglement."



A basic result from the theory of quantum information indicates that entanglement can't be observed unless the gravitational field through which the particles interact is in a quantum superposition. Therefore, observing the entanglement of the two particles is another means of demonstrating the quantum mechanical behavior of the gravitational field. In 2019 Rovelli published a paper with Marios Christodoulou of the Institute for Quantum Optics and Quantum Information Vienna (IQOQI) arguing that if gravity were indeed caused by deformations of the spacetime geometry, then measuring such entanglement would provide evidence that spacetime geometry can be put into superposition—that space and time, one may say, are quantum.

The 2017 proposal, and this convergence of spacetime physics with the field of quantum information, has caused a splash of experimental, theoretical and philosophical consequences. We are both members of a research consortium called Quantum Information Structure of Spacetime (QISS) that is working to elaborate theoretically and experimentally on these ideas. For instance, a group at IQOQI has been developing the experimental techniques that will be necessary for the entanglement experiment. Other groups in QISS have clarified the theoretical and philosophical significance of the experiment and proposed alternatives to measuring entanglement.

That the QISS collaboration involves philosophers such as Huggett may seem surprising. But there is a tradition of philosophical investigation of space and time that can be traced from antiquity through 17th-century polymaths Newton and Gottfried Wilhelm Leibniz, 19th-century scientist Henri Poincaré, Einstein, and many others. When foundational notions such as space and time need to be rethought, we need people who can bring in a high level of analytical and conceptual—that is, philosophical—clarity. For instance, Huggett recently explored the implications of gravitational entanglement in a book written with science philosophers Niels Linnemann and Mike D. Schneider.

THIS IS NOT THE FIRST TIME scientists have envisioned laboratory experiments meant to test possible quantum gravity phenomena. But all past proposals, as far as we can tell, involved either unobservably small or extremely speculative effects that aren't actually predicted by plausible hypotheses about quantum gravity. Rovelli remembers his surprise at first encountering the idea for the new gravity-induced entanglement experiment: a phenomenon that may well become testable and that we expect to be real.

There is still a long way to go over the next few years to carry out such trials (and there would be an even longer path toward enacting our own thought experiment). But if they can be successfully accomplished, they will test the low-energy domain on which almost all theories agree. If researchers find evidence for spacetime in superposition, then they will have the first direct evidence for the basic assumptions of our theories of quantum gravity. We will substantially rule out the possibility that gravity is classical, a significant and previously unexpected step forward. More than that, experimentalists would have reached a new horizon of the physical world, producing a region of spacetime that is observably quantum in a macroscopic laboratory. At last physics will have concretely entered a realm that for now remains a land of hypothesis.

If signs of superposition are not observed, the experiments will instead support speculations that gravity is intrinsically classical, confounding the expectations of much of the physics community and plunging a huge amount of work from the past 40 years into crisis. Such a result would require a significant revision of our understanding of the world and of the connection between quantum theory and gravity.

In either case, the effect would be momentous. ■

FROM OUR ARCHIVES
Quantum Gravity in the Lab. Tim Folger; April 2019. ScientificAmerican.com/archive


1

the Agenda Setters

Bringing Science to Life

ALZHEIMER'S DISEASE can rob us of our memories, our independence and our lives, and by 2050 a crushing wave of dementia could be costly enough to swamp healthcare systems and drag down entire economies.

TURNING THE TIDE ON ALZHEIMER'S

COLUMBUS CLUB AT UNION STATION | WASHINGTON DC | FEBRUARY 2024

Scientific American has partnered with the **Davos Alzheimer's Collaborative** to highlight a global effort that promises to turn the tide. In an exciting salon event, held in Washington DC's **Columbus Club** at Union Station in late February, leaders from science, industry, advocacy and healthcare policy discussed how dementia could be delayed for years or even prevented, and how healthcare systems must transform to support brain health for the world's aging population. This salon, hosted by Scientific American's Custom Media division, included two expert panels, opening remarks by DAC's founding chairman, **George Vradenburg (10)**, and ample pre- and post-event networking opportunities. Special guests, US Senators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Amy Klobuchar (1) and **Susan Collins (2)**, shared their personal stories of family members with Alzheimer's and policy initiatives they've spearheaded to support brain health.

Program participants also included: **Jeremy Abbate (9)**, Publisher, Scientific American; **Elias Zerhouni (3)**, Former Director, National Institutes of Health; **Suzanne Schindler (4)**, Associate Professor of Neurology, Washington University School of Medicine; **Jeffrey Burns (7)**, Professor of Neurology, University of Kansas Medical Center; **Phyllis Barkman Ferrell (8)**, Chief Impact Officer, StartUp Health Alzheimer's Moonshot; **Arindam Nandi (5)**, Health Economist, Population Council; **Terry Fulmer (6)**, President, John A. Hartford Foundation.

A SPECIAL COLLABORATIVE ISSUE, **THE NEW AGE OF ALZHEIMER'S** IS AVAILABLE AT: **SCIAM.COM/ALZ**

Vote, Then Act

The best antidote to the frustrations of national politics is a focus on local issues BY THE EDITORS

VOTING in local elections is critical for ensuring the best possible representation in the laws and actions that affect your daily life. But once your ballot is cast, getting involved in a local project allows you to flex your strengths for the betterment of society. Using your voice at public hearings or organizing neighbors can be invigorating and informative, and the actions you take on behalf of your town or city can deeply tie you to your community in a way that few other actions can.

Take environmental issues, for instance. Recent U.S. Supreme Court rulings have weakened the Environmental Protection Agency's ability to fight pollution and to use the best available science in enacting regulations. The situation makes it seem like efforts to fight climate change are hopeless. Even the most stubborn optimists—people who fight against apathy and encourage others to do the same—would be forgiven for wanting to tune out.

But depending on where you live, opportunities for involvement might be vast. Many cities already have made commitments to reduce greenhouse gases, but smaller, rural municipalities may not. One place to begin, if your town doesn't have a plan, is with the Global Covenant of Mayors for Climate and Energy, which provides municipalities of any size with tools and guidance to help limit climate change.

If your town already has a climate committee dedicated to setting goals and systems for tracking progress, reach out to see how you can help. There may be a local advocacy group you can join or, if time is an issue, support. If nothing like that exists, attend a town board meeting and ask your elected officials about their plans for developing resilience and adaptation strategies. Check for grants at the county, state and even federal level that can be applied to a local project. Town officials aren't necessarily stonewalling progress—they might be genuinely overwhelmed or unfamiliar with possible resources, and you can help bridge that gap. This work will give you clarity into the specific challenges of your community, which is often how people end up running for a board seat themselves.

Local environmental projects rooted in science will be trickier to find in areas where the phrase "climate change" is synonymous with "liberal agenda." You may even be in a place, such as Florida, where the state government is openly adverse to climate mitigation. But these obstacles give you a chance to get creative. If you live in a hilly area that has experienced repeated economic losses from river flooding, for example, speak out about how trees and shrubs are excellent forms of erosion control and should be protected as critical infrastructure. Look at meeting agendas to see what development projects are being proposed—and then organize your neighbors to fight extractive ones that will harm the environment while leaving your community more vulnerable.

Use the weight of your professional background to be powerfully persuasive: Civil engineers can poke holes in developers' plans, landscape architects can encourage native planting, wildlife biologists can explain why a certain habitat that might look unimportant plays a critical role for an endangered species, and attorneys can point out the disingenuous use of environmental laws that block climate-friendly policies such as congestion pricing and high-density housing. Medical professionals can speak to the harmful effects of pollution and excessive heat on health, and people who work in communications can write press releases and keep their communities informed on social media.

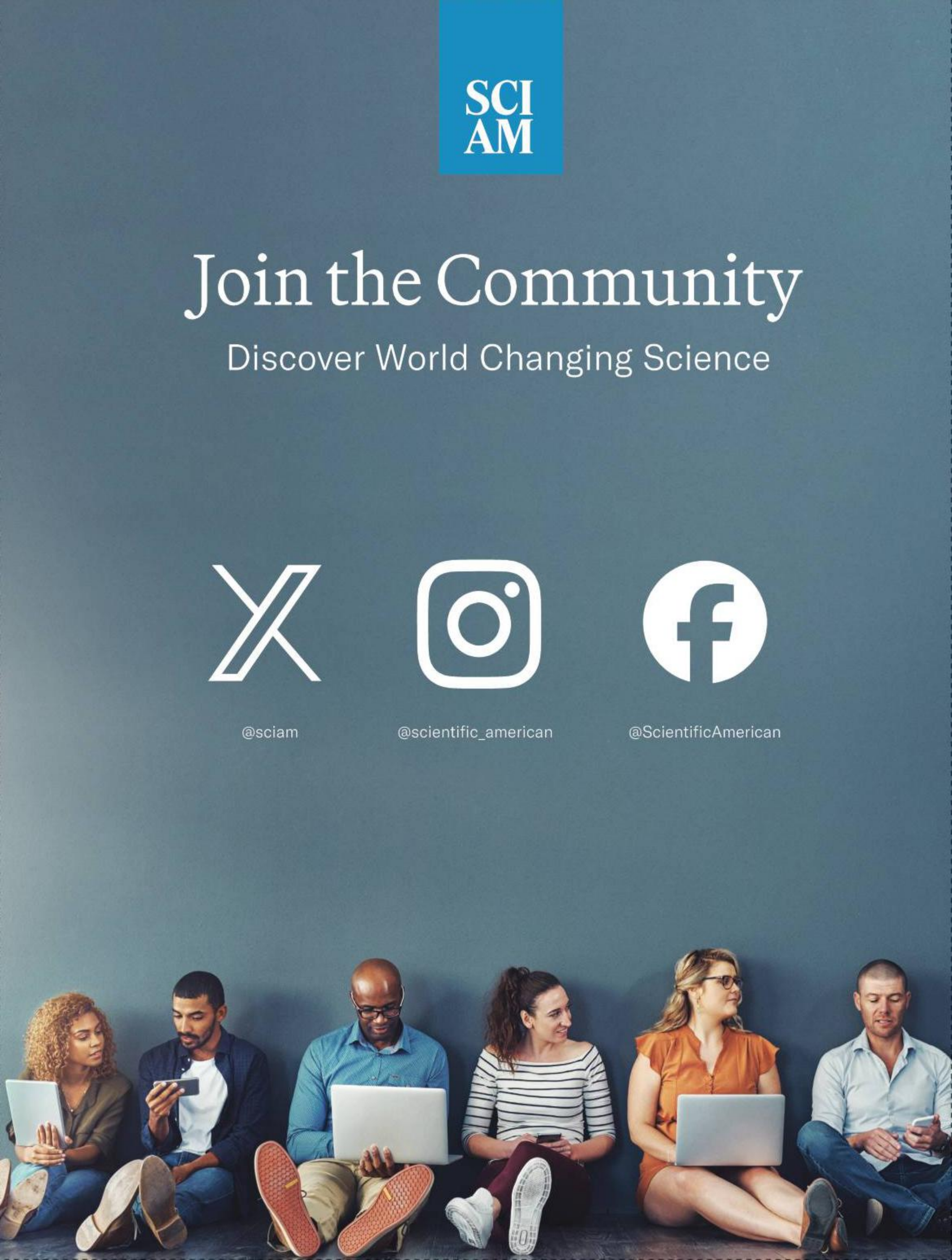
You're not limited to environmental issues. When you attend local meetings, you'll often hear about expiring funds that need to be used. Suggest that money earmarked for public health initiatives, for instance, be used to improve access to reproductive health care. If you've noticed that an important curriculum seems to be missing from your child's education, bring questions about it to a school board meeting.

As you get more involved in a local project—and, by extension, local politics—you will occasionally be baffled by feats of incompetence. You will feel exasperated by leaders who cling to a status quo that isn't working. You will encounter elected officials who routinely say "that's not my problem" instead of "let me look into that." You will wonder how important conflicts of interest—such as real estate agents being allowed to sit on planning boards—get overlooked.

But you will also encounter the unsung heroes of democratic society. The hydrologist at the state environmental conservation agency who patiently explains how pollution standards are enforced. The county attorney who tells you how to phrase a question on a Freedom of Information Law form so that it triggers the response you're looking for. These people will help you focus your efforts and invigorate your sense of agency for making change. They will also deepen your appreciation for public servants and the continuity of institutional knowledge.

The best part, though, might be experiencing a softening of the so-called partisan divide, the "us versus them" mentality that has severely alienated people from one another. Issues that seem deeply red or deeply blue at the national level aren't always so clear-cut at the local level. Solar farms, for instance, have been hugely successful in red areas and blocked in blue ones. Your neighbor who thinks federal agencies should stay out of his business might feel strongly about protecting a local trout stream—and will make an enthusiastic ally. Working together based on your shared values isn't just strategic; it's a balm for these divisive times.

In the end, what happens in federal politics does trickle down. There is much that our current judiciary throws back to state and local governments to decide. So this is your chance. Vote in November, all the way down your ballot. Then get out there and hold those down-ballot officials accountable—for what they do, whom they appoint, and how they improve your community and your future. ●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Climate Change Is Changing Astronomy

Astronomy's future may be slipping away—one climate disaster at a time BY SEVEN RASMUSSEN

"YOU'RE EVACUATING, RIGHT?" I tapped out on my phone in September 2022.

Hurricane Ian was bearing down on Fort Myers, Fla. My father, a Florida native and seasoned shelter-in-place hurricane survivor, texted me his grab-and-go list as he fled his home there: important paperwork, the dog, two outfits. "I'm not taking any chances with this one," he said.

Days later—when the debris was finally cleared from the roads—we learned just how devastating this one had been. The roof of his concrete riverside bungalow was still there. Two walls held it up. Everything inside the house was gone, and every house on the block had been swept through.

I was six months into my second astronomy postdoc then—the culmination of more than a decade of work. I had overcome the odds, summited the mountain of academia to gain a place at the forefront of exoplanet science. We had celebrated my success on my last trip to my father's house, as the golden trail of a Cape Canaveral rocket ripped a seam through the darkening skies. But even then, I had begun to wonder if my place among the stars meant that I was too far from Earth.

Those of us born after 1977 have never seen a cooler-than-average year. Since then, the frequency of major hurricanes has doubled, and the incidence of wildfires in northern and central California has quintupled. My generation—those who grew up with the now silenced clamor of insects and memories of snow days that don't seem to come around as often anymore—is neither the first nor the last to sound the alarm on our rapidly changing planet. The sirens have been wailing for decades.

You might think as a scientist I'd be especially attuned to the facts and figures and the dire future they portend. But after a while the sirens fade into the background, and the numbers start to run together. When I think of climate change, I do not think about the data. I think about the shoebox full of things my dad found on the lawn—two tuba mouthpieces, a waterlogged photograph of me at 11, a $2 bill in a Ziploc bag. I think about the big coat I bought when I moved to Indiana for graduate school that I never wore after my first year because every winter was warmer than the last. I think about the portable air-conditioning unit I had to buy when I moved to Tacoma, Wash., a city that wasn't built to endure sweltering summers.

Most of all, I think about those to come after me. Before Hurricane Ian, I had never questioned whether I was doing good in the world. Of course, I was contributing as an astronomer—it felt noble, studying what we can never touch or use, science simply for the sake of curiosity. But afterward, I had to ask myself whether it was enough. I could no longer shake the feeling that I was so occupied by other planets that I couldn't see the problems on mine.

As astronomers quietly ask themselves about the value of our federally funded science in a disastrously warming world, we must face the reality that the nation's highest halls of power will echo with those questions as well. Just this year Beltway policymakers sought cuts to both the Chandra X-ray Observatory and the Hubble Space Telescope, ones so severe that they would all but shutter the former. Such cuts are a product, in part, of growing pres-

Illustration by Thomas Fuchs

sures already constraining the budgets of NASA, the National Science Foundation, and other major public sources of funding for space science.

We must, then, consider the fate of our multibillion-dollar journeys into the solar system in a world increasingly subject to multibillion-dollar disasters. Although the projected spending peak has already passed for NASA's latest orbital eye to the sky—the Nancy Grace Roman Space Telescope, which is set to launch in 2027—the space agency has even grander plans on the horizon. They include the Artemis Program, which costs more than $7 billion annually, as well as an effort to retrieve rock samples from Mars that is currently undergoing a "back to the drawing board" replan after being deemed too expensive. But the project many astronomers are most excited about is NASA's next great space telescope, the Habitable Worlds Observatory (HWO), slated to launch in the early 2040s after a multidecadal development at a projected cost of some $11 billion.

Here's the problem: by the 2040s the world as we know it now will no longer exist. And with those multibillion-dollar crises on the rise—being just one category from climate change's myriad possibilities for fiscal ruin—funding for fixes must come from somewhere. In the 1980s natural disasters that cost more than $1 billion (inflation-adjusted) occurred at an average rate of 3.1 per year, with 297 annual deaths, compared with 17.8 events per year in 2017–2021, with 911 annual deaths.

Might Roman be NASA's final foray into ambitious orbital observatories? Will HWO make it, unscathed, to its notional launchpad later this century? The cost for each of the space missions so many of us love is comparable to that of a single climate disaster, a single recovery from an event that now can occur more than 20 times a year. As such calamities become commonplace, space science might begin to look like a luxury we can no longer afford.

Staving off climate change's worst effects falls most immediately on the national governments and multinational corporations—fossil-fuel companies chief among them—that collectively brought us to this impasse. But after decades of "top-down" failures, we must take matters into our own hands—to push our warming world and ourselves onto a better trajectory from the "bottom up."

Today, for better or worse, my father's house has been rebuilt just as it was, 20 feet from the water, awaiting the next "once in a century" storm. But I have uprooted myself. I left my second postdoc—gave away my textbooks, parceled out my in-progress research, closed out my tab-clogged web browser for the last time—and traded it all in for an adjunct professorship. Now I spend my days teaching whoever walks into my classroom about not just the stars above but how they are connected to the Earth below.

Astronomy is a joy—a miraculous expression of a universe seeking to know itself. I want to see new astronauts on the moon. I want to learn whether Mars once had life. I want to know whether we're not alone in the galaxy. All this—and much more—is possible, but the prospects diminish as our global ecosystem degrades. For every step we take to defend that joy, we must take another to defend our climate. Each of us should pause to think about what that looks like for ourselves and our communities. But not for too long—we can leave a better future for those to come only by acting now. ●

Seven Rasmussen is a professor at Tacoma Community College, where she teaches physics, astronomy and astrobiology. She is author of the forthcoming book *Life in Seven Numbers: A Journey into Astrobiology and the Drake Equation* (Princeton University Press, 2025).

When I think of climate change, I see the shoebox full of things my dad found on the lawn—a waterlogged photograph of me at 11, a $2 bill in a Ziploc bag.

Improving with Age

Contrary to stereotypes, many older adults maintain cognitive skills and improve in some areas

BY LYDIA DENWORTH

AS I WATCHED MY PARENTS' generation reach their 80s, I was struck by the dramatic differences among them. A handful suffered from dementia, but many others remained cognitively sharp—even if their knees and hips didn't quite keep up with the speed of their thoughts.

That observation runs counter to prejudices about aging, which were highlighted early in the 2024 presidential race between elderly candidates, but these biases permeate society in general. "The belief about old people is that they're all kind of the same, they're doddering, and that aging is this steady downward slope," says psychologist Laura Carstensen, founding director of the Stanford Center on Longevity. That view, she says, is a great misunderstanding.

Instead research highlights the very differences I noticed. In our 40s, most people are cognitively similar. Divergences in cognition appear around age 60. By 80 "it's quite dramatically splayed out," says physician John Rowe, a professor of health policy and aging at Columbia University's Mailman School of Public Health. Yes, there will be a group diminished by dementia and cognitive decline, but in general the 80-somethings "include the wisest people on the planet," Carstensen says.

Focusing on only those with poor brain health misses more than half the population. Rowe led research showing that in the six years after turning 75, about half of people showed little to no change in their physical, biological, hormonal and cognitive functioning, whereas the other half changed quite a lot. A longer-term study followed more than 2,000 individuals with an average age of 77 for up to 16 years. It showed that the three quarters who did not develop dementia showed little to no cognitive decline.

Some of this is related to genetics. Studies of successful aging have shown that genes account for 30 to 50 percent of physical and cognitive changes. But factors like a healthy way of life and good self-esteem are also consequential. So to an extent, Rowe says, "this is really good news because it means that you are, in fact, in control of your old age."

Research has also busted the myth that there is no upside to aging past 70 or so. "We have found very clearly that there are things that improve with age," Rowe says. The ability to resolve conflicts strengthens, for instance. Aging is also associated with more positive overall emotional well-being, which means older adults are more emotionally stable than younger adults, as well as better at regulating desires.

The normal aging process does bring changes to the brain, says Denise Park, a neuroscientist at the University of Texas at Dallas. There is some shrinkage in the frontal lobes and some damage to neurons and their connections. Cognitive processing slows down. Yet that slowdown is usually on the order of milliseconds and doesn't always make a meaningful difference in daily life. And to compensate, older people activate more of the brain for tasks such as reading. "Older adults will often forge additional pathways" for particular activities, Park says. "Those pathways may not be as efficient as the pathways that younger adults use, but they nonetheless work."

The cliché that age brings wisdom is also backed up by science. "Where older adults really shine is in their knowledge," Park says. If you think of the brain as a computer, "there's a lot more on the hard disk," she says. Older adults can draw on their experience and often have much better solutions to problems than younger adults. "Frequently that can give them an edge that is unexpected," Park says.

That edge shows up in decision-making and conflict resolution. One study asked several hundred people to read stories about personal and group conflicts. The study, published in 2010 in the *Proceedings of the National Academy of Sciences USA,* found that participants older than 60 were more likely to emphasize multiple perspectives, to compromise, and to recognize the limits of one's own knowledge. Carstensen's observations reinforce these conclusions. "The decisions that people make as they get older tend to be ones that take into consideration multiple factors and multiple stakeholders," she says. Older adults are less likely than younger people to see the world in stark black-and-white terms. Carstensen says that when responses in such studies are rated by observers who don't know how old participants are, the older people's answers are seen as wiser.

Such wisdom may be the result of a gradual shift in perspective, Carstensen says. As we age and become more aware that time is short, we focus more on the positive. A meta-analysis combining data on more than 7,000 older adults found they were significantly more likely than younger adults to lean toward the positive versus the negative when processing information.

The COVID pandemic has showcased this contrast. In a 2020 survey of nearly 1,000 adults, Carstensen and her colleagues found that the older adults were better able to cope with the stresses of the pandemic, despite being one of the groups at highest risk of health complications and death.

The fact is that different parts of the body can age at different rates in the same person. Someone who stumbles on stairs may do so because of creaky knees, not cognitive decline. If someone has a healthy brain, age alone might be considered a definite asset. "If you were to take the kinds of decisions presidents make and compare them to the kinds of skills older people have versus younger people, I put my money on older people," Carstensen says.

Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American.* She is author of *Friendship* (W. W. Norton, 2020).

Illustration by Jay Bendt

No Spoilers, Please!

Curiosity makes people hungry for knowledge—but not always in a hurry

BY ABBY HSIUNG, JIA-HOU POH, SCOTT HUETTEL AND ALISON ADCOCK

ASK ANY BIRDER, and they'll tell you about the thrill of identifying a new species. Recently a tapping sound outside a window alerted one of us (Hsiung) to the presence of a striking, unfamiliar woodpecker in a nearby tree. Woodpeckers are fairly common in Hsiung's neighborhood in the southeastern U.S., but this one looked different. Its head was plumed with large red feathers, and it was huge—the size of a crow. Curious, she whipped out a phone app and soon became acquainted with the Pileated Woodpecker.

Scientists have often seen curiosity as motivation to discover new information and to initiate and facilitate learning. That framing suggests that curiosity is all about acting now—that it drives us to find answers as soon as possible. In previous research, when people were able to choose whether to receive their highly anticipated answer to a question now or later, they generally opted for the fastest path to resolution.

This impatience for answers aligns with what psychologists think is a main function of curiosity: to reduce uncertainty. The state of not knowing or of recognizing a gap in your knowledge can be discomfiting, like an itch that needs to be scratched. This feeling of uncertainty then motivates a search for information that, when obtained, is met with relief and satisfaction.

But this picture of curiosity is incomplete. Consider how people watch a murder-mystery movie. As the tension builds, viewers want to know the identity and the motive of the murderer—but unlike the desire to identify a strange new bird, most don't feel the urge to reach for a phone and resolve that curiosity. Instead people savor the twists and turns of the plot as they gather more information. The desire to avoid premature resolution is so common that viewers explicitly label details in online conversations with "spoiler alerts" to help one another preserve uncertainty.

In a study published in the *Proceedings of the National Academy of Sciences USA,* we explored whether there are multiple flavors of curiosity. We found that although piquing interest can indeed drive an urgent desire for answers, it can also elicit more patience, setting people up for those moments of discovery.

We asked more than 2,000 people aged 19 to 76 years to watch a series of short videos that we created for an online experiment. Each video started with a blank screen. A line would then appear and squiggle around, gradually taking a shape. Imagine, for example, an animated line that begins to wiggle upward and downward, tracing a series of triangles reminiscent of a crown or mountain range. The line then extends, forming an oval around the triangles, resembling an Easter egg. Then, just as you start to feel certain you know what the finished drawing will be, long, pointy spikes are sketched at the top, revealing the true subject: a pineapple.

While our study participants watched each video, we asked them to report how curious they were about what the drawing would become and to guess what the drawing was going to turn into. They also told us, on a scale of 1 to 100 from least to most, how confident they felt about their prediction and how much joy or frustration they felt. Those replies let us gauge how curiosity changed as people saw more of a video. We also gave them the choice to either keep watching the drawing slowly unfold or jump to the end of the video, revealing the entire picture immediately.

Interestingly, when participants were more curious about what the drawing would become, they were more likely to continue watching rather than skipping ahead to the answer. In other words, greater inquisitiveness motivated people to slow down, be patient and invest in experiencing the winding path to resolution. Although past work has shown that more intense curiosity increases people's motivation to get information, our study found that it also contributes to greater avoidance of "early" answers.

Abby Hsiung studied information seeking at Duke University. She is now a researcher at Meta.

Jia-Hou Poh is a postdoctoral researcher at Duke. He studies the cognitive and neural mechanisms supporting learning and memory.

Scott Huettel is a professor of psychology and neuroscience at Duke. He focuses on the behavioral and brain mechanisms of cognition and decision-making.

Alison Adcock is director of the Center for Cognitive Neuroscience and an associate professor of psychiatry and behavioral sciences at Duke. She researches neural mechanisms of motivation and memory.

Illustration by Justin van Gend

Why do our findings differ from those of other studies? One important factor is what happens while people wait for more details. Watching events unfold over time, as in our animations, may be less uncomfortable than simply wanting a missing answer—imagine if Hsiung had just stared at the woodpecker while gaining no new information about it. Further, curiosity may feel different when people assume that answers are on the way. When opportunities to seek information abound, curiosity may favor its patient accumulation. But when it seems like waiting will yield limited information, people might prefer immediate resolution.

Our experiment also revealed that curiosity was highest at two key points: first, when uncertainty was the greatest, and second, when people were very close to identifying the drawings. To us, this signaled that curiosity seemed to evolve along with the question a person was asking, such as with a shift from an exploratory musing ("What could this drawing be?") to a more focused query ("Is this going to be an Easter egg?").

The desire for information also seemed to feel different across the journey to resolution. When uncertainty was greatest, curiosity was experienced with joy. But during the second peak, as people got closer to the big reveal, curiosity coincided with frustration, perhaps like the sensation when a word is right on the tip of your tongue. As curiosity evolves over different lines of questioning, the emotional tone may shift from playful happiness to urgent discomfort.

So as people watched the video, curiosity would grow, change in emotional timbre and then decline with resolution. Yet regardless of how curiosity changed, we found that greater curiosity encouraged engagement in the process and led to a greater desire to let a video play out rather than skipping to the answer.

Our work underlines the complexity of curiosity, opening new avenues for research to explore its varieties. Thinking about curiosity as going beyond the need for quick answers also highlights the power of what happens when we engage with uncertainty: having to ponder and anticipate answers can improve learning and memory, and curiosity can facilitate brain states that help us encode new information. Learning new things can be tough, but harnessing curiosity can help us savor the process of learning and delight in overcoming challenges as much as we like working out a whodunit—all in due time. ●

As curiosity evolves over different lines of questioning, the emotional tone may shift from playful happiness to urgent discomfort.

Supernova Scars

Stellar explosions regularly shower Earth with radioactive debris

BY PHIL PLAIT

A SUPERNOVA would have to be fairly close to Earth to pose any real threat to our planet. For astronomers, though, "close" means something different than it does for other people. In this case, a supernova within about 160 light-years, or 1.5 quadrillion kilometers, would qualify.

On a human scale, that's a nearly unfathomable distance. On a galactic scale, it's in our immediate neighborhood. Still, it's a long walk, and supernovae are relatively rare, occurring roughly once a century in a large galaxy like the Milky Way. So the odds are good that any given exploding star will be far from Earth and will do nothing more for us than put on a pretty light show (if we can see it at all through the thick dust that shrouds parts of our galaxy).

But note my weasel words "any given exploding star." The thing about rare events is that, with enough time, they will happen. We again must think on cosmic scales: Generously speaking, one supernova per century is maybe once per human lifetime. But galaxies (and Earth) have been around for billions of years. That's more than long enough for the probability of a too-close-for-comfort supernova to become a certainty. I personally wouldn't bet against it. After all, we have convincing physical proof that it has happened in our planet's past.

In 2016 two teams of astronomers published a pair of papers with startling results in the journal *Nature:* they found elevated amounts of iron-60 in two different layers of ancient sediment from the deep seafloor. Each of those iron-60-enriched layers marks a time during the past nine million years when Earth was bombarded by a nearby supernova.

A vast, expanding cloud of debris from a supernova is seen in x-ray and optical light by the Chandra X-ray Observatory and the Hubble Space Telescope, respectively.

NASA/CXC/GSFC/B. J. Williams et al. (*x-ray*); NASA/ESA/STScI (*optical*)

Iron-60 is a radioactive isotope of iron that decays into cobalt-60 with a half-life of 2.6 million years. This half-life means that if you start with a pure sample of iron-60, in 2.6 million years half of it will have decayed to cobalt-60. In another 2.6 million years, the remaining iron-60 in the original sample will have again decayed by half, leaving only one quarter of the starting amount of iron-60 and so on. Scientists can use this decay rate to get relatively accurate measurements of when the iron-60 formed. That is important because we know of only one natural place where this isotope can be forged: in the nuclear fires of a supernova.

In the first *Nature* paper, scientists examined interstellar dust on the ocean floor and found two peaks in the amount of iron-60 in sediments that were deposited around 7.5 million and 2.5 million years ago. (In a separate study, from 2016, another team of scientists found iron-60 in fossil bacteria on the ocean floor. That isotope was also consistent with a peak dating to circa 2.5 million years ago.) Curiously, the increases in iron-60 weren't the sharp spikes expected from a single supernova. Instead, in each case, the increases were spread out over more than a million years, implying that multiple supernovae contributed to each episode. The researchers' models indicated the material spent about 200,000 years coasting through interstellar space before it fell to Earth.

In the second *Nature* paper, scientists who were affiliated with the first team used these data to estimate where in space the supernovae were located. Iron-60 is created when massive stars explode. Such stars give new meaning to "cradle to grave," cosmically speaking, because they are born in giant gas clouds and die just a few million years later, still cocooned inside them.

This second *Nature* study flagged the most likely culprit for both supernovae as the Scorpius-Centaurus association, a loosely bound clump of young stars that are currently located about 390 to 470 light-years from Earth. Many of these stars are quite massive and exactly the kind that explode at the end of their life. Moreover, our sun sits near the middle of what's called the Local Bubble, a huge cavity carved out of the interstellar material that floats between stars in the galaxy. The bubble was inflated by supernovae in the Scorpius-Centaurus association some 14 million years ago and probably required the work of 14 to 20 such exploding stars. This timeline fits well with the iron-60 peaks observed in ocean sediments.

The scientists found that two supernovae might have contributed to the most recent peak, with one exploding 2.3 million years ago and the other doing so 1.5 million years ago. Both stars would have been about 300 light-years from Earth when they exploded. The amount of iron-60 in the sediments is actually quite small—very roughly 100,000 atoms per gram of material. (A gram of sediment has something like 10^{22} atoms in it, so the iron-60 makes up only an extremely tiny portion.) But the astonishing thing is that debris from exploding stars quadrillions of kilometers from us is here at all.

Bear in mind that iron-60 also makes up a small fraction of the material ejected during a supernova. The rest of the ejected matter—more than 10 octillion metric tons of it—is also accelerated outward at speeds of tens of millions of kilometers per hour. As matter expands away from the blast site, it thins out, so by the time the ejecta from a nearby supernova reaches Earth, perhaps a few hundred metric tons might rain on our planet over a length of time. That might sound like a lot, but about the same amount of meteoric material slams into our atmosphere every day. So supernovae aren't appreciably adding to Earth's weight, nor are they a big danger to us in this way.

Still, the takeaway is stunning: Every few million years a supernova happens close enough to Earth to shower us with radioactive debris. That means that over the lifetime of our planet, we've been hit thousands of times with ashes from exploding stars, and some of that material has probably been close enough to cause some global damage.

In the specific case of the most recent nearby supernova, although humans weren't around back then, several of our near ancestors, such as *Australopithecus afarensis,* were. One particular member of that species, nicknamed Lucy, walked on Earth about three million years ago. She might have missed that particular event, but her descendants may have gazed up into the sky and wondered about the astonishingly bright light that appeared there, brighter by far than any other star, as bright as the full moon. It would've been luminous enough to be seen by day and cast shadows at night.

And here we are, millions of years later, still wondering about the same thing. The difference is that now we have the tools to both examine and understand the profound impact these cosmic explosions have on our planet.

Phil Plait
is a professional astronomer and science communicator in Virginia. He writes the *Bad Astronomy Newsletter.* Follow him on online.

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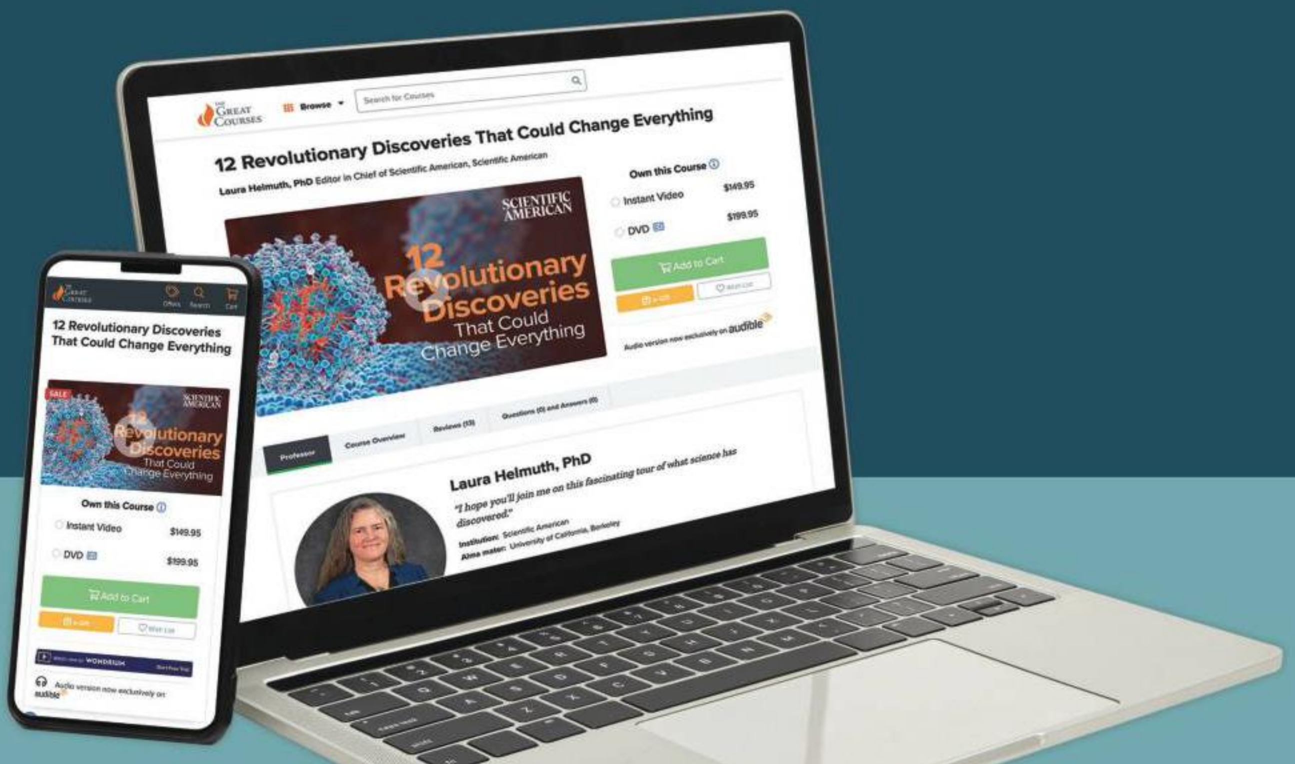

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Computation Foretold

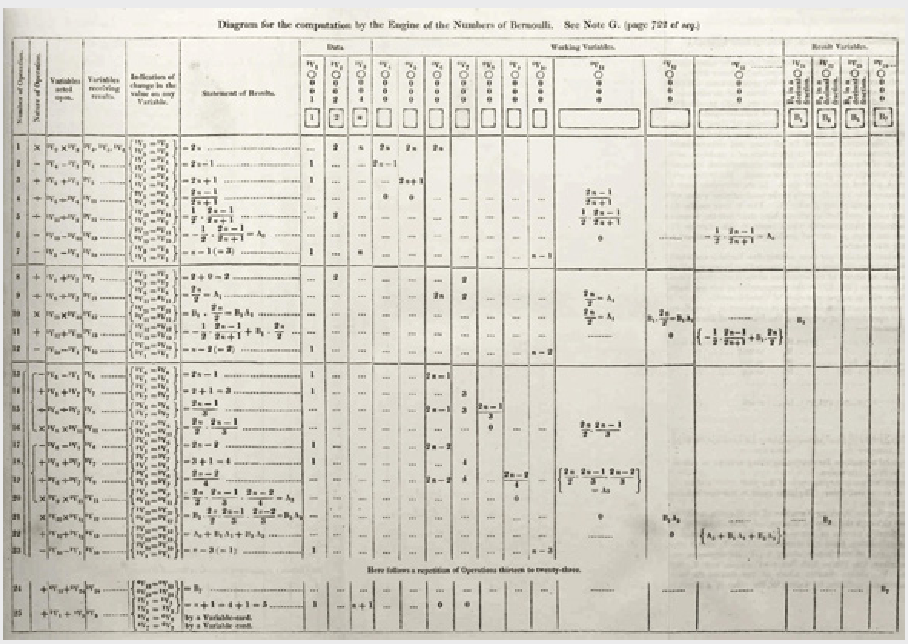
Ada Lovelace's wisdom about the first general-purpose computer is buried in the appendix of a paper BY JACK MURTAGH

MANY FIELDS OF SCIENCE have a foundational document: Isaac Newton's *Principia* for the physics of classical mechanics, for example, or Charles Darwin's *On the Origin of Species* for evolutionary biology. But only computer science can claim its foundation hides in endnotes.

Augusta Ada King, Countess of Lovelace, better known as Ada Lovelace, was commissioned in 1842 to translate a paper about the world's first general-purpose computer. She appended her own annotations, which ran three times longer than the original article and completely eclipsed it in terms of technical meat and philosophical insights. The impressive foresight they reflected established her as the first person to envision the universal capabilities of computers that we take for granted today.

Lovelace's dad is now familiar to people around the world, but she never knew him personally. Lord Byron, celebrated for his English Romantic poetry, was by all accounts a rotten husband and absent father. (After first meeting Lord Byron in 1812, aristocrat Lady Caroline Lamb apparently called him "mad, bad and dangerous to know.") Lovelace's parents' brief and tumultuous marriage ended with Lady Byron, née Annabella Milbanke, accusing her husband of abuse and infidelity a mere five weeks after his daughter's birth. Although they never met again, Lord Byron had at least two lasting effects on his daughter. For one, she maintained a curiosity about him and his work and perceived much of her later scientific worldview through a poetic lens. Second, Lady Byron attempted to shield Lovelace from inheriting her father's erratic temperament by steering her away from literary studies and instead fostering her interest in science and math.

Jack Murtagh writes about math and puzzles, including a series on mathematical curiosities at *Scientific American* and a weekly puzzle column at Gizmodo. He holds a Ph.D. in theoretical computer science from Harvard University. Follow Murtagh on X @JackPMurtagh



This scheme for computing Bernoulli numbers on an analytical machine was devised by Ada Lovelace and is the first published computer program.

The Picture Art Collection/Alamy Stock Photo

The defining partnership of Lovelace's intellectual life would be with polymath Charles Babbage, whom she met when she was 17. In 1833, the year they met, Babbage had begun designing the first general-purpose mechanical computer, called the analytical engine. The idea captivated Lovelace, and the two became close friends and collaborators.

Had Babbage ever managed to build it, his analytical engine would have been a marvel to behold. Sketches and spec sheets depict an intricate beast with rattling gear columns towering 15 feet high, lever panels cranking in lockstep and thousands of moving parts churning together in a kind of steampunk orchestra. Though unrecognizable as your laptop's ancestor, the device remarkably contained most of the same components found in modern computer architecture. It had a central processing unit called a mill to carry out arithmetic operations, memory storage, input capabilities for reading data and programs, and even a printer.

Keep in mind that the era predated electronics, so steam would have powered all of this functionality. Each gear column stacked 40 gears with 10 teeth apiece, labeled 0 through 9. The gear positions corresponded to a 40-digit number, much like the disks in a combination lock. The mill could crunch these numbers through complicated procedures involving the rotation and swapping of gears. But the secret sauce that separated the analytical engine from its predecessors was that it was programmable.

The design drew inspiration from the Jacquard machine, which attached to a loom and disrupted the 19th-century textile industry by automating weaving through punch-card technology. Like the Jacquard machine, the analytical engine could have read instructions in the form of holes punched into card stock. Babbage had built a prototype for an earlier device called the difference engine (currently on display at the Museum of Science in London), which could mechanically calculate a preset suite of operations such as certain logarithms and trigonometric functions. He abandoned it because he saw greater potential in a machine that could be programmed to perform arbitrary calculations.

Programmability elevates a machine from a mere calculator to a computer. The analytical engine would have been able to choose which instruction to follow based on the outcome of a previous computation—a skill called conditional branching. This capability would have allowed the machine to carry out advanced instructions using things such as "if-else" statements and loops seen in today's programming languages. Although Babbage understood the power of programmability, he still viewed the analytical engine as a purely mathematical device. Only Lovelace foresaw the true potential of the computer.

Ten years after Lovelace first learned of the analytical engine, she was commissioned to translate a paper on the topic written by mathematician and engineer Luigi Federico Menabrea (who would go on to be Italy's seventh prime minister). Possessing much more detailed knowledge of the engine than Menabrea, Lovelace corrected his errors and added seven endnotes of her own, which alone constitute a watershed document in the history of computation.

Many retrospectives focus on "Note G" because it contains the first published computer program. Lovelace's program calculates Bernoulli numbers, which play a critical role in a branch of math called analysis. Her calculation method used more computational steps than necessary, but she chose this tack deliberately to show off the power and flexibility of the machine. Although many credit her as the first computer programmer, some historians contend that unpublished programs predated her notes and that technically Note G contains not a program as we'd name it today but rather an execution trace—a record of every operation performed during the execution of a program. I find such quibbles moot because I'd argue that the moniker "first computer programmer" undersells the wisdom found in the rest of her notes.

Ada Lovelace, sometimes called the world's first computer programmer, was also the first to foresee the potential of analytical machines.

API/Gamma-Rapho via Getty Images

Babbage saw the analytical engine as a mathematical device. After all, it primarily stored and operated on numbers. But Lovelace recognized that a machine designed to crunch numbers could do much more if the numbers represented other things. For example, she wrote in the endnotes, "Supposing, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent." Now, some 180 years later, generative artificial-intelligence tools such as Suno and Udio can compose music from text-based prompts.

Lovelace's insight marks a profound conceptual leap that wouldn't be formalized until the work of Alan Turing a century later: Fundamentally, computation involves the manipulation of symbols according to rules. There's no limit on what those symbols can represent. This idea is built into Turing's mathematical model of computation, and it originated with Lovelace. We take for granted today that the same bits of 0s and 1s encode every type of media—text, images, audio, video—but it's hard to fathom that this future was envisioned before the first computer had even been built.

Lovelace also explicitly discussed artificial intelligence, kicking off a debate that defines the modern era. She concluded in her endnotes that the analytical engine would not be intelligent because it wouldn't originate anything, arguing that "it can do whatever we know how to order it to perform." Turing challenged Lovelace by name in his seminal paper on "thinking machines." Although he conceded that computers merely do what they're told, Turing suggested they still have the power to surprise us. He acknowledged that Lovelace never had an opportunity to interact with a computer and so lacked the advantage of experiencing such surprise for herself. In today's AI landscape, many now believe that machines can exhibit intelligence (although holdouts from Lovelace's camp are not hard to find). The fact that Lovelace even entertained the question of whether a clanging heap of cogs that had been sketched only on paper would be intelligent shows how ahead of her time she was.

Ultimately Babbage's contentious relationship with the British government meant that he never secured enough funding to bring the analytical engine to life. It's funny to contrast Lovelace's prophetic words about the potential of computers with a quote from the U.K.'s then prime minister Robert Peel: "What shall we do to get rid of Mr. Babbage and his calculating machine? Surely if completed it would be worthless as far as science is concerned?" ●

Can Coral Reefs Be Saved?

Mass bleaching events threaten corals worldwide

BY MEGHAN BARTELS

OCEAN HEAT IS KILLING CORALS at such high rates that in April scientists declared Earth was in its fourth global bleaching event—the second in a decade. The announcement came from the U.S. National Oceanic and Atmospheric Administration and the International Coral Reef Initiative.

Despite their plantlike appearance, corals are animals, and their vibrant colors come from microbes that live inside the creatures and offer them a range of services. Some of these symbionts produce sugars through photosynthesis, some provide other nutrients, and some protect the corals' health. But when corals are stressed, they eject their symbionts—an often fatal move.

Corals can bleach in response to a range of threats, but today they most commonly do so because water temperatures are too high for them. Throughout late 2023 and into 2024 global sea-surface temperatures have been at record highs in many areas, and it's been a disaster for corals. During the summer of 2023 in the Northern Hemisphere, widespread bleaching occurred in the Florida Keys, the Caribbean and the eastern Pacific. The Southern Hemisphere's last summer added much of the Great Barrier Reef to that casualty list. And earlier this year scientists warned that the same event might be occurring throughout the Indian Ocean and the waters north of Australia.

SCIENTIFIC AMERICAN spoke with Terry Hughes, a marine biologist at James Cook University in Australia, about the global bleaching event and what the future may have in store for the planet's coral reefs.

An edited transcript of the interview follows.

Why do corals bleach?

Extensive large-scale or global bleaching events are triggered by exceptionally warm sea temperatures driven by anthropogenic heating, primarily from fossil-fuel burning and from deforestation. Nothing else is happening at that kind of scale, and there's nowhere to hide from global warming. Even the most remote and most pristine coral reefs are vulnerable to these repeated bouts of bleaching.

Bleaching is only one of several stress responses by corals. Sometimes there isn't actually enough time for bleaching to unfold; the corals just die from heat stress directly—they literally cook. We saw that in the summer of 2023 in the Florida Keys and throughout the Caribbean, where sea temperatures were off the charts.

We also see a phenomenon where a coral becomes unusually colorful; it glows. And that's caused by a protein produced by the coral in a desperate bid to stay alive. Those proteins act as a sort of sunscreen, but it's not a very effective way of defending against record temperatures. These corals typically die within a week or two of becoming very colorful.

Because bleaching doesn't directly kill these animals, could some bleached corals survive?

It's impossible that all of the corals that are bleached will survive. Bleaching is not necessarily fatal, but often it is. And the likelihood of the corals dying depends on the severity of the bleaching and how long it lasts. A mass bleaching event is, by definition, a mass mortality event. The reality is that we are losing literally billions of corals on the world's coral reefs.

How do scientists evaluate bleaching?

There are two ways to measure the extent of bleaching. One is directly, through observations of individual reefs, and the other is indirectly, using satellite data, which is what NOAA does. Satellite data tell you how hot the water has been for how long. So we

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Illustration by Shideh Ghandeharizadeh talk about the accumulated heat stress over the summer months, and you can use that level of heat stress from satellites as a proxy for the intensity of bleaching. It's good to ground truth with data from underwater or aerial surveys of the extent of bleaching.

I have conducted aerial surveys of the Great Barrier Reef three times. It takes about eight days of flying in a small plane or helicopter to crisscross about 1,000 reefs and score the extent of bleaching. And that allows us to produce a map of the entire Great Barrier Reef showing which portions of the reef have been bleached. The map has lots of red dots [that indicate bleaching] on it this year and very, very few green dots where there was no bleaching. This year 75 percent of the Great Barrier Reef has bleaching. And it's the size of Italy or Japan, so it's a big piece of real estate. For 75 percent of it to be bleached in just one event—bearing in mind that this is the fifth [local bleaching event] in eight years—is really very shocking.

Soon I'll be at southern Great Barrier Reef sites that I have been studying since 1985, and I'm dreading it. The reef has been exposed to the highest level of heat stress it has ever seen. We already know that 80 percent of the corals at these sites are bleached, and I'm fully expecting the majority of those to be dead or dying.

When we fly over a reef with no bleaching, we literally cheer. It's very stressful to spend an entire day in a plane flying over, say, 200 reefs, all of which are severely bleached. It's quite a confronting sight, but it's the only way to get the big picture at the scale of the Great Barrier Reef. Tragically, in the Caribbean and particularly in the Florida Keys, it's no longer possible to do aerial scores of bleaching because there aren't enough corals left.

As the Northern Hemisphere heads into summer again, what is the outlook for how long this global bleaching event might last?

Winter temperatures on the world's coral reefs have also been at record levels. That's not enough to trigger bleaching, but if you have a hot winter, then sea temperatures at the start of summer are already halfway to stressful levels. And we saw that on the Great Barrier Reef in 2016 and 2017, where we had the first example of back-to-back coral bleaching in two consecutive summers.

The climate modelers are telling us that that will become the norm by the middle of the century, depending, of course, on greenhouse gas emissions. So the concerning thing about these bleaching events, whether they're global or regional in scale, is that the gap between one bleaching event and the next is getting shorter and shorter. And those gaps are critically important for any recovery that can take place. They're the window of opportunity—particularly for the fast-growing corals that are better at recovery—to regain a foothold.

What does "coral recovery" mean?

Some people refer to bleached corals' regaining color as their recovering—that's a physiological recovery four to six months in timescale. But ecological recovery means the replacement of dead corals by new live ones, ideally of the same species and eventually of the same size. When a 50- or 100-year-old coral dies, it takes at least that length of time to replace it. And we just don't have that kind of time anymore.

The world's coral reefs are becoming a checkerboard where the history of recent bleaching and its recurrence are changing the condition of those reefs. A reef that's lucky might not have bleached for five to 10 years. A reef that's unlucky might have bleached three times in the past decade.

That history affects how much coral there is, and it also affects the mix of coral species. The great untold story about these bleaching events is how they have already transformed the mix of species because species vary in heat tolerance: some are very tolerant; some are very susceptible. And then some species are better at breeding and make more babies than others.

The severity of the current bleaching event on the Great Barrier Reef, ironically, is because of rapid recovery on many of those reefs since the last time they were bleached. The corals that come back the quickest are also among the most heat-sensitive. It's a bit like fire in a terrestrial landscape, where a forest is destroyed and flammable grasses come back quicker than the trees do, which makes that ecosystem more vulnerable to drought and fires. Exactly the same thing is happening on the world's coral reefs.

Changing the mix of species is changing the entire ecology of the world's coral reefs. And of course, corals are critically important for the habitat that they provide to fish and crustaceans, all the iconic biodiversity that coral reefs are famous for. When you lose a lot of corals, which we're seeing, sadly, everywhere now, it alters the entire ecosystem. It's like having a rainforest without the rainforest trees.

What do we need to do to keep corals alive in the long term?

There's only one answer to that question: we need sea temperatures to stabilize. We've got to ideally reach somewhere between 1.5 to two degrees Celsius [2.7 to 3.6 degrees Fahrenheit] for global average warming. Every fraction of a degree matters in terms of the number of corals that are killed by global warming.

Can restoration and planting efforts help, or are they a red herring?

One of the most confronting aspects of the current global event is that it is destroying existing attempts to restore coral reefs. In Florida, coral nurseries literally cooked. People rescued some by moving them into an aquarium, but that's hardly a long-term solution. We see the same thing happening on the Great Barrier Reef, where many of the intervention trials are now failing. Putting more corals back out is really a death sentence as temperatures keep rising.

I think the most optimistic thing you could say about planting corals is that you can do it at a very small scale, but it's quite labor-intensive and expensive, and it will inevitably fail the next time you get a severe bleaching event. We shouldn't kid ourselves that we can save coral reefs by planting a few acres of corals.

What's your message or outlook, given the declaration of this fourth global bleaching event?

We shouldn't give up on the world's coral reefs; they're just too valuable to lose. But restoration is not the way to save them. The way to save them is to deal with greenhouse gas emissions, and that's, of course, much, much harder. ■

Adrift in Theories

Science means being able to admit you were wrong BY NAOMI ORESKES

MANY TRAITS that are expected of scientists—dispassion, detachment, prodigious attention to detail, putting caveats on everything, and *always* burying the lede—are less helpful in day-to-day life. The contrast between scientific and everyday conversation, for example, is one reason that so much scientific communication fails to hit the mark with broader audiences. (One observer put it bluntly: "Scientific writing is all too often ... bad writing.") One aspect of science, however, *is* a good model for our behavior, especially in times like these, when so many people seem to be sure that they are right and their opponents are wrong. It is the ability to say, "Wait—hold on. I might have been wrong."

Not all scientists live up to this ideal, of course. But history offers admirable examples of scientists admitting they were wrong and changing their views in the face of new evidence and arguments. My favorite comes from the history of plate tectonics.

In the early 20th century German geophysicist and meteorologist Alfred Wegener proposed the theory of continental drift, suggesting that continents were not fixed on Earth's surface but had migrated widely during the planet's history. Wegener was not a crank: he was a prominent scientist who had made important contributions to meteorology and polar research. The idea that the now separate continents had once been somehow connected was supported by extensive evidence from stratigraphy and paleontology—evidence that had already inspired other theories of continental mobility. His proposal did not get ignored: it was discussed throughout Europe, North America, South Africa and Australia in the 1920s and early 1930s. But a majority of scientists rejected it, particularly in the U.S., where geologists objected to the form of the theory and geophysicists clung to a model of Earth that seemed to be incompatible with moving continents.

In the late 1950s and 1960s the debate was reopened as new evidence flooded in, especially from the ocean floor. By the mid-1960s some leading scientists—including Patrick M. S. Blackett of Imperial College London, Harry Hammond Hess of Princeton University, John Tuzo Wilson of the University of Toronto and Edward Bullard of the University of Cambridge—endorsed the idea of continental motions. Between 1967 and 1968 this revival began to coalesce as the theory of plate tectonics.

Not, however, at what was then known as the Lamont Geological Laboratory, part of Columbia University. Under the direction of geophysicist Maurice Ewing, Lamont was one of the world's most respected centers of marine geophysical research in the 1950s and 1960s. With financial and logistical support from the U.S. Navy, Lamont researchers amassed prodigious amounts of data on the heat flow, seismicity, bathymetry and structure of the seafloor. But Lamont under Ewing was a bastion of resistance to the new theory.

It's not clear why Ewing so strongly opposed continental drift. It may be that having trained in electrical engineering, physics and math, he never really warmed to geological questions. The evidence suggests that Ewing never engaged with Wegener's work. In a grant proposal written in 1947, Ewing even confused "Wegener" with "Wagner," referring to the "Wagner hypothesis of continental drift."

And Ewing was not alone at Lamont in his ignorance of debates in geology. One scientist recalled that in 1965 he person-

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Illustration by Scott Brundage

ally “was only vaguely aware of the hypothesis” [of continental drift] and that colleagues at Lamont who were familiar with it were mostly “skeptical and dismissive.” Ewing was also known to be autocratic; one oceanographer called him the “oceanographic equivalent of General Patton.” It wasn’t an environment that encouraged dissent.

One scientist who did change his mind was Xavier Le Pichon. In the spring of 1966 Le Pichon had just defended his Ph.D. thesis, which denied the possibility of regional crustal mobility. After seeing some key data at Lamont—data that had been presented at a meeting of the American Geophysical Union just that week—he went home and asked his wife to pour him a drink, saying, “The conclusions of my thesis are wrong.”

Le Pichon had used heat-flow data to “prove” that Hess’s hypothesis of seafloor spreading—the idea that basaltic magma welled up from the mantle at the mid-oceanic ridges, creating pressure that split the ocean floor and drove the two halves apart—was incorrect. Now new geomagnetic data convinced him that the hypothesis was correct and that something was wrong with either the heat-flow data or his interpretation of them.

Le Pichon has described this event as “extremely painful,” explaining in an essay that “during a period of 24 hours, I had the impression that my whole world was crumbling. I tried desperately to reject this new evidence.” But then he did what all good scientists should do: he set aside his bruised ego (presumably after polishing off that drink) and got back to work. Within two years he had co-authored several key papers that helped to establish plate tectonics. By 1982 he was one of the world’s most cited scientists—one of only two geophysicists to earn that distinction.

In the years that followed, Lamont scientists made many crucial contributions to plate tectonics, and Le Pichon became one of the leading earth scientists of his generation, garnering numerous awards, distinctions and medals, including (ironically) the Maurice Ewing Medal from the American Geophysical Union. In science, as in life, it pays to be able to admit when you are wrong and change your mind. ■

Rocket Launch Laconic

Countdown metronomic
Astronomic diastolic
Mental state cyclonic
Praying atheist ironic

Cacophony chaotic
Blastoff billowing iconic
Liftoff! Spacecraft aeronautic
Rocket supersonic

Clapping histrionic
Grinning idiotic
Hugging kiss platonic
Gazing up hypnotic

Orbit episodic
Flawless avionic
Systolic now harmonic
Recapping rhapsodic

Nighttime mind spasmodic
Therapeutic tonic
Crashed-out catatonic
Dreaming astronautic

Julie Dillemuth is a picture book author, screenwriter and poet with a Ph.D. in geography. She lives in Santa Barbara, Calif., where the rocket launches from Vandenberg Space Force Base rattle her windows from 60 miles away.

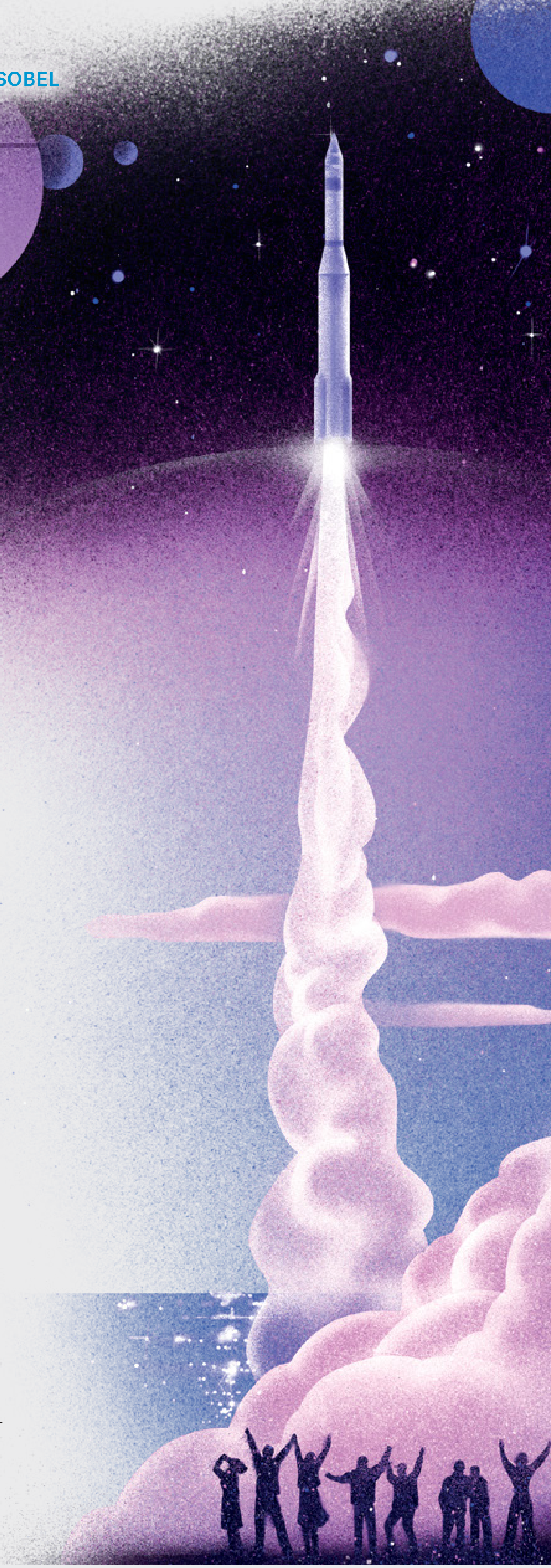


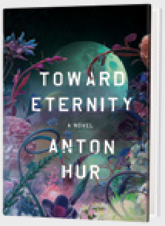
Illustration by Masha Foya

Immortal in Name Only

A parable about the hybridization of people and AI clings to poetry while marching toward devastation **BY JEFF VANDERMEER**

FICTION Anton Hur's *Toward Eternity* blends the music of science and of poetry to tell a tale of future love, war, and tiny robots known as nanites. Like a reverse-engineered allegory, the novel attempts to fuse the forward momentum of the reader's care for its most compelling character, Yonghun Han, with high-concept ideas about biotechnology, the future of Earth and the question of identity.

Han is "Patient One." He's been remade in a laboratory in Cape Town, South Africa, by Mali Beeko, a doctor who has cured Han's cancer through nanite cellular replacement, which essentially renders the recipient immortal. Although Han's body is new, a scar from a previous kitchen accident has returned to his skin, as if the physical can be affected by the power of the mind. When Han disappears from Beeko's Singularity Lab into thin air, no one has an explanation—and they're equally mystified when he reappears. This returned Han believes he is "not Yonghun Han. I am whatever came back with his body." Han finds Beeko's journal and continues to write in it in an attempt to make sense of his experience. This is the conceit that carries the book forward through time as various characters inherit the journal and propel the narration into the extremely far future.



Toward Eternity: A Novel
by Anton Hur.
HarperVia, 2024 ($26.99)

The early chapters are suffused with emotional resonance thanks to Han's extraordinary love for his husband, Prasert, a scholar of 19th-century poetry who has been dead for a decade. There are flashback scenes of Prasert ceding the last bite of a meal to Han and giving Han a back rub, all of which convey a genuine sweetness and authenticity that is rare in depictions of love on the page. The not-Han that has come back grapples with Han's memories of that relationship in ways that question personhood and identity: "I am the recursion, the vessel necessary for the love to return, a love so great it has overcome the death of its previous vessels to live in this world again, searching for what it had lost."

The tenderness of that bond also opens a space for Hur to explore the confluence of science and the arts. Han creates an artificial-intelligence entity named Panit to help him better understand poetry. A discussion between Han and Panit about Christina Rossetti's "Winter: My Secret" showcases the novel at its best. In a sense, Han is talking to a version of himself, having trained the AI on his experience of poetry, and the scene should be solipsistic. Instead this conversation about Rossetti "teasing a secret but never revealing it" evokes, again, Han's deep love for Prasert.

Soon enough the notebook is passed to Meeko's Patient Two. Ellen, a musician, has a more aloof tone, and her perspective serves as a useful contrast to Han's remembered warmth, accentuating it greatly. As the poetry cedes pride of place to music, Ellen's encounter with doubles of herself presages a future nanite-person takeover of the world while giving clues to the mystery of Han's disappearance and reappearance. When Panit, the AI, gets time with the notebook, we learn more about Meeko's experiments. But as the novel slips officially into the future with part two ("The Future"), other kinds of slippage occur.

The science of fiction writing has few hard rules except that almost anything can work. The scaffolding of an idea can carry a novel through to the end, even without maintaining the psychological richness Han's early

Illustration by Alex Eben Meyer

> Are we really so resigned to catastrophe that we just trudge forward, hoping to eke out some entertainment before the end?

chapters accomplish so well. But characterization—committing to interiority and depth of character—is harder to sustain without the author's constant and devoted attention. A novel that set out to be pathos becomes almost exclusively a science experiment.

It begins with a Panit-Han hybrid, a fusion persona in physical form that overuses the word "ghost" to a pathological extent. When this hybrid pines for a child and encounters a doomed love, the scenes echo Han's relationship with Prasert, though now to lesser effect. As the journal passes from hand to hand in the future, it feels as if the pages are becoming washed out, the entities writing it less and less knowable.

As the narrative progresses into the far future, the structure becomes harder to follow. The story swaggers through time and character perspectives, the connective tissue often lacking or delivered to the reader through explanatory dialogue. I would have loved to encounter more tension between the rising dominance of AI and the technology's huge drain on resources and thievery of people's intellectual property and labor. These issues are present but mostly through sheer extrapolation.

Part of what makes the novel increasingly hard to follow is the blurriness of the scenes. For the most part, Hur doesn't provide much description of the future settings except when noting there are "trees" or "rocks." What'll be perhaps most glaring to readers who appreciate contemporary science fiction is that Hur largely sidesteps the evolution and consequences of our climate crisis. Instead of exploring those rough edges, he mostly obliterates them by using the device of a widespread nuclear war. A war that brings mass extermination is hell, all right, but with its harshness blasted out, the future doesn't feel quite as real or fully realized.

The novel comes to a halt in a long section written from the viewpoint of Delta, a version of Panit-Han's daughter grown in a nanite vat. Delta has just done something terrible to humanity, yet there's little sense of the weight of Delta's actions in the storyline. Instead of something incendiary, something radical, we get mostly more dialogue reasonably explaining the future.

Are we really so resigned to catastrophe that we just trudge forward, hoping to eke out some entertainment before the end? This tone of amiability that creeps into the writing seems to be meant to please the reader, to dull the pain of humans losing who we are. I often wished that the language were sharper.

Writing about the effect of poetry is different than *being* poetry. For a while *Toward Eternity* is poetry, until entropy sets in. By the time the novel reaches its end, the carrying forward of the beloved Han feels attenuated, grasping. The burning core of the narrative—that beautifully depicted relationship in the early chapters—is a distant flame you no longer feel the heat of. The things that make us uniquely human are simply too far in the past.

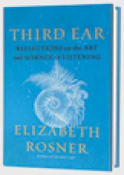
Jeff VanderMeer is author of *Hummingbird Salamander,* the Borne novels and the Southern Reach series. His 2014 book *Annihilation* won Nebula and Shirley Jackson Awards and was adapted into a movie by Paramount. His next book, *Absolution,* will be published in October 2024.

IN BRIEF

Night Magic: Adventures among Glowworms, Moon Gardens, and Other Marvels of the Dark
by Leigh Ann Henion. Algonquin, 2024 ($30)

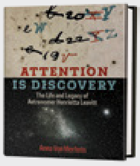
I recently returned from a camping trip with legs covered in bug bites and a newfound awareness of my reliance on artificial light and the glow of electronic devices. It seems author Leigh Ann Henion had a similar epiphany and sought an antidote by venturing into the Appalachian Mountains after hours. *Night Magic* chronicles her journey to "re-center darkness" through experiencing the living things that thrive in it: spotted salamanders that perform mating dances before an audience of fairy shrimp and tricolor bats that see through sound. Henion's vivid style of nature writing and complementary self-reflection are reminders that witnessing the extraordinary can be as easy as shifting your bedtime back an hour and going outside. *—Maddie Bender*

Third Ear: Reflections on the Art and Science of Listening
by Elizabeth Rosner. Counterpoint, 2024 ($27)



As a child of Holocaust survivors growing up in a multilingual immigrant household, author Elizabeth Rosner became a careful listener of both the spoken and the unspoken. Her expansive, fluid meditation on so-called third-ear listening—a deeply attuned, intuitive way of perceiving the world that transcends the physically audible—is rooted in personal experience, but the contemplative vignettes explore our sonic universe. Drawing together topics ranging from the rise of podcasting to the vibration-detection sensitivity of an elephant's foot, this poignant exploration of the hidden depths of the soundscapes around us reveals the importance of listening with more than just our ears. *—Dana Dunham*

Attention Is Discovery: The Life and Legacy of Astronomer Henrietta Leavitt
by Anna Von Mertens. MIT Press, 2024 ($34.95)



Fans of *Hidden Figures* and *The Glass Universe* will appreciate Anna Von Mertens's captivating portrait of Henrietta Leavitt and the Harvard Computers, who laid the foundation for modern cosmology at the turn of the 20th century. Blending complex science with human-interest stories, Von Mertens celebrates the constellation of women scientists who discovered how to calculate galactic distances and classify stars by chemical composition. The writing occasionally veers into textbook territory, but Von Mertens includes vibrant illustrations and archival documents that help to bring these astronomical legends to life on the page. This deeply researched book is ultimately an homage to the process of observation and meaning making in science. *—Lucy Tu*

Our Stormy Solar Future

Space weather is heating up in our current solar cycle peak

TEXT BY CLARA MOSKOWITZ
GRAPHIC BY MATTHEW TWOMBLY

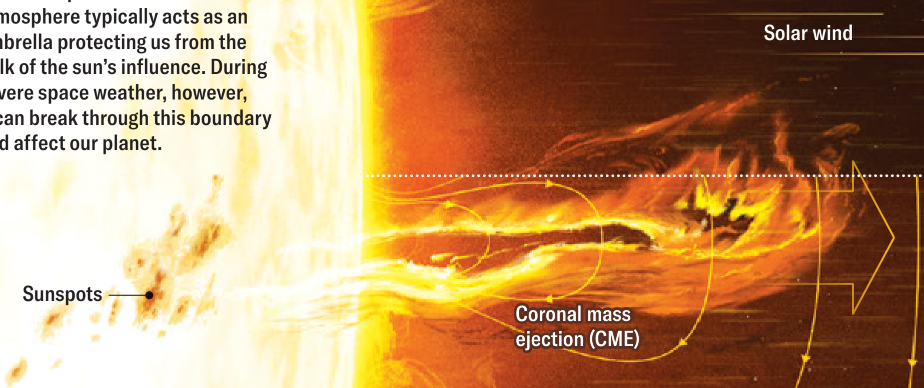
AURORA SIGHTINGS MAY become more common, and satellite communications and power grids could be disrupted, as solar activity peaks. Our nearest star is always volatile, but its magnetic action waxes and wanes on an 11-year loop. The sun is thought to be in a peak now, although scientists will need another year or two to analyze data before they can say for sure. During this high point we should see more sunspots (dark areas where the sun's magnetic field reaches the surface) and solar storms (ejections of energy from the sun that reach into space and can affect Earth).

During a storm, energy explodes from the sun in the form of light and particles (called a solar flare) and a plasma and magnetic field (called a coronal mass ejection, or CME). If a CME hits Earth's magnetosphere, it can wreak havoc on our planet's magnetic field, injecting energy, plasma and particles and heating up and distorting Earth's upper atmosphere, the ionosphere. All of this chaos can hinder radio signals between satellites and induce strong electric currents that can damage power grids. On the plus side, we often get a nice view of the Northern and Southern Lights as a surge of particles hits Earth's atmosphere at the poles.

"We need to better prepare for space weather," says heliophysicist Lisa Upton, who co-chaired the NASA/NOAA Solar Cycle Prediction Panel for the current cycle. "Write your congresspeople and tell them to support solar physics."

WHAT IS SPACE WEATHER?
The amount of energy, radiation and plasma streaming off the sun into space—collectively known as the solar wind—varies as the sun's magnetic activity changes. Extreme events, such as CMEs and strong solar flares or storms, generate space weather. Earth's atmosphere typically acts as an umbrella protecting us from the bulk of the sun's influence. During severe space weather, however, it can break through this boundary and affect our planet.

BEFORE THE STORM
The solar wind is a constant flow of charged particles and radiation emitted from the sun. Usually Earth's magnetosphere deflects this flow.

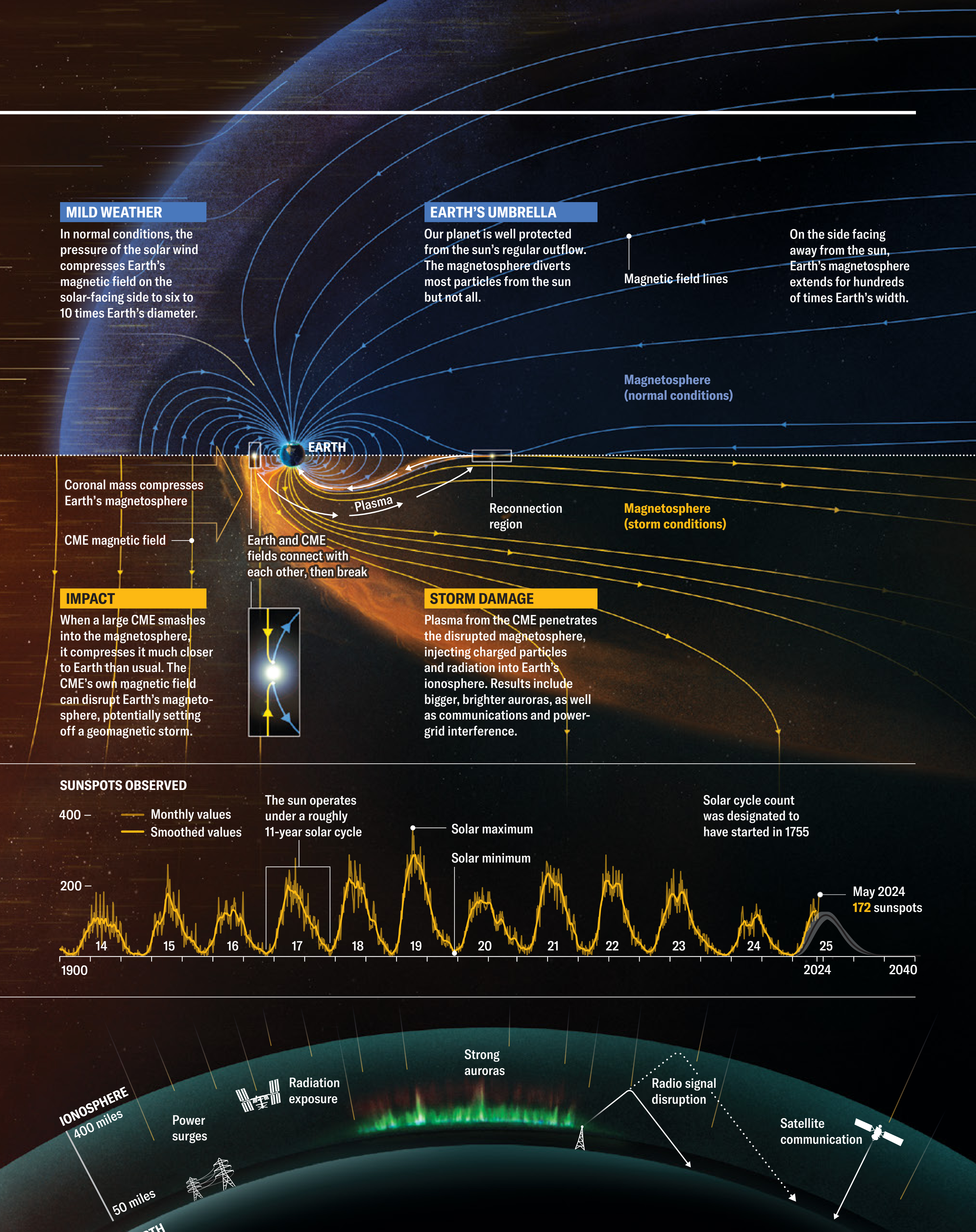


A BREWING STORM
Sunspots, relatively cooler areas where the sun's magnetic field protrudes through its surface, appear in active regions and correspond to increased magnetic strength.

EJECTION
A CME is a violent eruption of plasma that ejects billions of tons of material into space. Particles from the fastest ejections can reach Earth in one day.

FORECASTING
Like the climate on Earth, space weather has its own seasons, referred to as solar cycles. About every 11 years the sun's magnetic field reaches its maximum activity level. During solar minimum we observe around one CME a week, but during maximum, where we are right now, we see about two to three a day. Scientists can predict solar activity by observing the number of sunspots visible on our star. During minimums we may see just a few sunspots or even none, whereas during solar maximum we can expect up to 200 at a time.

EFFECTS
Space weather affects the density and turbulence of Earth's ionosphere. As radio signals travel through this layer of the atmosphere, its changing thickness may send waves on distorted paths, affecting communications transmission. And an influx of particles streaming toward Earth can cause brighter and more widespread auroras, as well as surges in power grids that lead to outages.


MILD WEATHER
In normal conditions, the pressure of the solar wind compresses Earth's magnetic field on the solar-facing side to six to 10 times Earth's diameter.
EARTH'S UMBRELLA
Our planet is well protected from the sun's regular outflow. The magnetosphere diverts most particles from the sun but not all.
Magnetic field lines
On the side facing away from the sun, Earth's magnetosphere extends for hundreds of times Earth's width.
Magnetosphere (normal conditions)
EARTH
Coronal mass compresses Earth's magnetosphere
Plasma
Reconnection region
Magnetosphere (storm conditions)
CME magnetic field
Earth and CME fields connect with each other, then break
IMPACT
When a large CME smashes into the magnetosphere, it compresses it much closer to Earth than usual. The CME's own magnetic field can disrupt Earth's magneto-sphere, potentially setting off a geomagnetic storm.
STORM DAMAGE
Plasma from the CME penetrates the disrupted magnetosphere, injecting charged particles and radiation into Earth's ionosphere. Results include bigger, brighter auroras, as well as communications and power-grid interference.
SUNSPOTS OBSERVED
400 –
200 –
Monthly values
Smoothed values
The sun operates under a roughly 11-year solar cycle
Solar maximum
Solar minimum
Solar cycle count was designated to have started in 1755
May 2024
172 sunspots
14
15
16
17
18
19
20
21
22
23
24
25
1900
2024
2040
IONOSPHERE
400 miles
50 miles
EARTH
Power surges
Radiation exposure
Strong auroras
Radio signal disruption
Satellite communication

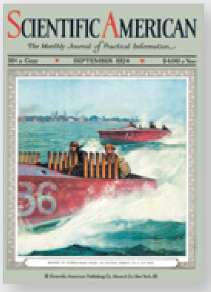
50, 100 & 150 Years

MYSTERIOUS MERCURY: LIKE MOON OR MARS?

1974 "In the five months since the spacecraft Mariner 10 floated past Mercury, quantitative analyses of its instrumental data and 2,300 high-resolution photographs have revealed some surprises. The early photographs indicated that Mercury strongly resembles the moon. Measurements of the planet's mass, however, indicate that unlike the moon (and like the earth) it must have a heavy core. The principal visible difference is that Mercury has a few scarps about three kilometers high, some of which are more than 500 kilometers long; there is no counterpart on the moon. Perhaps most puzzling is that Mercury, like the moon and Mars, is heavily cratered on one side and has wide, flat plains on the other. Why three of the five bodies in the inner solar system should be so asymmetrical is not clear."

A DIFFERENT KIND OF CLOCK RADIO

"Technological advances have relegated pendulum clocks to unreliable antiques. One such instrument, however, has been modernized by Laurance M. Leeds, who coupled his 80-year-old Seth Thomas wall clock to a quartz-crystal oscillator. The clock now ticks off the time to an accuracy of about one second per year. Week after week the old pendulum now 'notches up' the 60th second of every minute in almost exact coincidence with the signals of radio station WWV, on which the National Bureau of Standards broadcasts accurate time and frequency data."



VITAMIN D, WHITE CHEMICAL OF LIFE

1924 "Food chemists have known about four or five vitamins for quite a few years, but [Walter] Eddy, [R. R.] Kerr and [Ralph] Williams of Columbia University are the first who have isolated any one of them. Vitamin D, sometimes called Bios, is the one without which you are in danger of having rickets. Vitamin D when isolated is a crystalline, white substance that looks like a dose of quinine. You cannot eat it straight. If you do, according to Kerr, you will regret it. The chemists say they don't intend either to license the process of manufacture or to make it for sale themselves. They hope to show some day that life is simply a chemical process."

SPIDERS AND OXEN PREDICT THE WEATHER

1874 "Curiously, a large number of animals seem able to predict the weather. Some of their actions appear to be more governed by reason than instinct, due to the moisture in the air or various atmospheric influences; the common garden spider, on the approach of rainy or windy weather, will be found to shorten and strengthen the supporting guys of its web, lengthening the same when the storm is over. Sea gulls assemble on the land, as they know that the rain will bring earthworms to the surface. Yet there is a large variety of actions of which it is hardly possible to give a satisfactory explanation. Coming rain is foretold by the peacock uttering frequent cries, by the woodpecker lamenting, by parroquets babbling and by geese running around uneasily. When a storm is at hand, swine will carry hay and straw to hiding places, oxen will lick themselves the wrong way of the hair, colts will rub their backs against the ground, crows will gather in crowds, frogs croak and change color to a dingier hue, dogs eat grass and rooks soar like hawks."

RAINING ANTS AND HERRING

"An ant rain recently happened in Cambridge, England. At about six o'clock in the evening, shortly after a rise in temperature, a shower of ants in countless millions settled in the streets, covering the pavements. There is believed to be no record of an ant rain of such magnitude. We have also found a large number of cases of showers of fish, generally explicable by the occurrence of water spouts, which draw them up, whence carried by strong gales to the land. In Scotland rains of herrings have frequently occurred, the fish in some instances falling far inland. A shower of frogs fell near Toulouse in 1804. The rat shower of Norway was traced to a whirlwind, which, overtaking an enormous army of the rodents during their annual journey from a hilly region to the lowlands, whisked them up and deposited them in a field at considerable distance."

1974, Sioux Population: "Lone Dog's 'winter count,' painted on the inside of a buffalo robe, chronicles 71 turbulent years in the migratory life of the Yankton tribe of the Sioux from the winter of 1800–1801 to that of 1870–1871. Each year is represented by a symbol recalling some memorable event. The record begins near the center and spirals outward counterclockwise."

Scientific American, Vol. 231, No. 3; September 1974

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“THE END OF THE LAB RAT?,” by Rachel Nuwer, should have said that outside researchers have used Emulate’s chips to create more than 30 additional models with cells from their labs, not about 70 such models.