SCIENTIFIC AMERICAN

Lost Worlds of the Dinosaurs

Sand Mafias

Quantum-Proof Encryption

The Milky Way's Secret History

New star maps reveal our galaxy's turbulent past

FEBRUARY 2024
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SCIENTIFIC AMERICAN

FEATURES

ON THE COVER
The Milky Way galaxy has been harboring secrets. For years scientists thought our cosmic home was stable and unchanging, but incredibly detailed star maps are now expanding that picture. Astronomers have recently discovered signs of smaller galaxies falling into the Milky Way and other tumultuous events. The new story of our galaxy is one of constant change, what astronomers call "evolving disequilibrium."

Illustration by Ron Miller.

Nigel Killeen/Getty Images (*Milky Way seen in New Zealand*)

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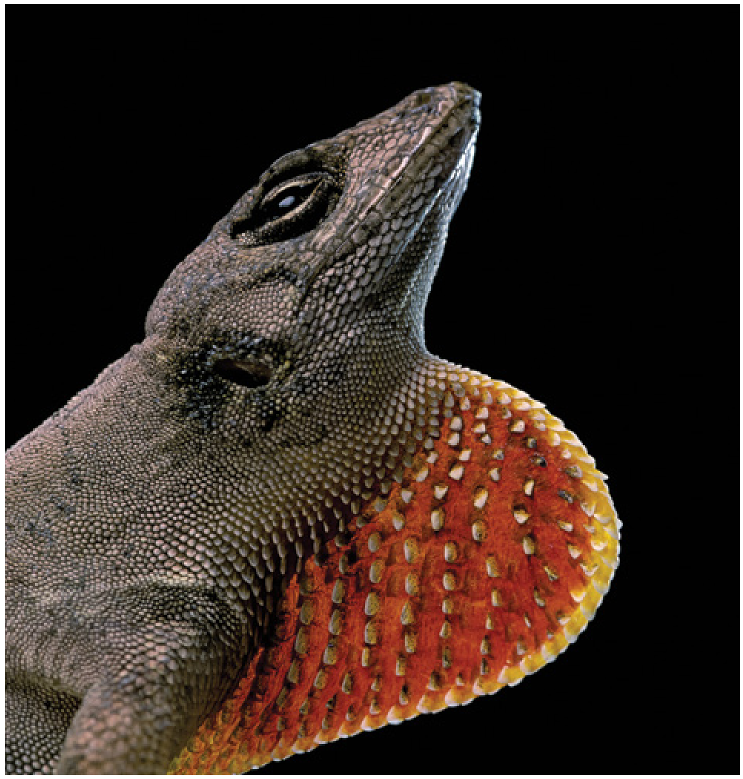

Paul Starosta/Getty Images

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Illustration by Izhar Cohen

The Milky Way, Dinosaur Lives and Intelligence

ONE OF THE BIGGEST MYSTERIES of the universe is why there is a universe at all. According to particle physics, the big bang should have created equal amounts of matter and antimatter, and they should have immediately canceled each other out. But here we are! We're lucky enough to exist, and we get to live in a time when fundamental questions can be asked and potentially answered scientifically. Physicist Luke Caldwell on page 52 narrates how he and his colleagues made the most precise measurement ever of a property of electrons that could help explain the existence of everything.

It's tempting to think that our big old human brains are uniquely able to learn, store information, and use know-how to make decisions and solve problems. But bizarrely, recent research suggests that even rudimentary clumps of nonbrain cells—from the skin or the heart, for instance—can remember experiences and act on their knowledge. This work is leading to new ideas about the evolutionary origins of intelligence, as author Rowan Jacobsen writes on page 44. The field, called basal cognition, is full of startling examples that may change how you think about thinking.

The clock is ticking toward a time when quantum computers will be able to hack today's most common and sophisticated security systems. The clock has a name, the Y2Q clock, and the projected date when we'll no longer be able to shop safely online or share encoded messages securely is April 14, 2030 (but that's just a rough guess). The National Institute of Standards and Technology challenged inventors a few years ago to come up with "quantum-resistant" cryptography. On page 36, mathematician and writer Kelsey Houston-Edwards discusses how the winners of that contest propose using lattice mathematics and other strategies to keep today's secrets safe from tomorrow's quantum computers.

Do you remember the first time you saw a faint band of stars across the sky and realized that was the Milky Way? No matter how many times you notice it, it's awesome to know you're seeing our own spiral galaxy from within. That sight might be a little more awesome after reading author Ann Finkbeiner's description on page 20 of unprecedented star-tracking projects that have generated a new map of the Milky Way. Our galaxy's history turns out to be much more tumultuous and chaotic than expected. One astronomer sums up our new view as "the single largest increase in astronomical knowledge in, like, forever."

Sand mining is a serious and growing environmental threat that has not gotten as much attention as deforestation or overfishing. Most of the sand is used in concrete, and the world is mining it much faster than it can be replenished. Sand dredging disrupts coastlines and rivers, and the industry is full of transnational corruption. Writer David A. Taylor goes inside the world of illegal and (kinda) legal sand mining on page 60 and shows how investigators are trying to stop the most dangerous practices.

Some of the most dramatic fossil discoveries in the U.S. have been made in the badlands of Montana. Paleontologist Kristina A. Curry Rogers and geologist Raymond R. Rogers on page 28 take us on their journey to look at some of the humbler—but no less vital—fossil finds: teeth, fish scales, parasites and small bones. They describe in loving detail what it was like to live in the steamy, buzzy, monstrous time of the dinosaurs. ⬢

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

KRISTINA A. CURRY ROGERS AND RAYMOND R. ROGERS
LOST WORLDS OF THE DINOSAURS, *PAGE 28*

At around six years old, Kristina A. Curry Rogers read a story in a kids' magazine about the discovery of fossilized dinosaur eggs and babies in Montana. She immediately decided to become a paleontologist, and decades later she became a specialist in long-necked dinosaurs, such as sauropods. During a field expedition in Zimbabwe, she met Raymond R. Rogers, a geologist who studies how fossils form. "She fell in love with me," Ray laughs, and the two got married a few years later.

It turned out that their lines of research were complementary, too. As professors at Macalester College in Minnesota, they work together to uncover the lost worlds of the Cretaceous dinosaurs found in modern-day Montana, which they detail in a feature in this issue. When trying to imagine this bygone, swampy ecosystem, Kristi says, "I think of the soundscape," with buzzing mosquitoes and the splash of turtles diving off logs. These seaside swamps would be familiar to us, filled with crocodiles, frogs and fish. "If you time traveled there," Ray says, "you would not know you're in the Cretaceous until you bumped into a dinosaur."

Jeff Thole

ANN FINKBEINER
OUR TURBULENT GALAXY, *PAGE 20*

Since the 1980s science writer Ann Finkbeiner has been covering the cutting edge of cosmology—the big bang, the structure of the universe, the evolution of galaxies. But through it all, "I looked down on our own galaxy," she says of the Milky Way. "I thought it was just too trivial and, you know, just puny." After all, what can we extrapolate about the laws of the universe by looking at a single galaxy? But when *Scientific American* space and physics editor Clara Moskowitz asked Finkbeiner if she wanted to write about recent efforts to map the Milky Way, Finkbeiner was hooked almost immediately. "I thought, 'I look at the sky every night, and I don't have a clue about what's going on up there!'"

Finkbeiner lives in Baltimore, where her view of the stars is limited, but she grew up in the countryside and remembers her excitement when she realized the hazy line across the night sky was our own galaxy. While reporting on new maps of the Milky Way for this article, she gained a new appreciation for our galactic home: "it's not what we thought it was."

MARK SMITH
SAND MAFIAS, *PAGE 60*

In his 20s and early 30s Mark Smith held many different jobs. He was a greenkeeper at a golf course, a mail carrier, and an employee in skate and record shops. By his mid-30s he wanted a change—"I didn't really have anything to lose," he says—and he applied to an illustration program at a university. "It's the only thing I think I could have really poured my heart into," he says. Now an artist based in Exeter, England, he illustrated this issue's feature article by journalist David A. Taylor on the illegal mining and selling of sand from coasts and rivers. Smith, who has traveled to Morocco's beaches multiple times to surf, was immediately fascinated by the country's "sand mafias" and set out to translate the article into images.

The topic fit well with a shift he's been making in his artistic approach, moving away from more conceptual, abstract work toward narrative illustrations, which tell immersive stories and can be "a bit more weighty," he says. Smith doesn't try to explain how he decides to depict these visual tales—it's a form of artistic expression that defies words: "That's the magic, for me, and why I enjoy it so much."

FEDERICA FRAGAPANE CASCADING CLIMATE IMPACTS, *PAGE 86*

From vintage books to museum exhibits to nature, Federica Fragapane is a collector of beauty. "If I see something beautiful, I take pictures because I know that I might use it as inspiration." Being an information designer is the perfect challenge for Fragapane, who once thought that pursuing a career in design meant leaving behind her love of storytelling and science. Her graphics often convey narratives about human rights abuses and climate change. Three of her works, including one on the killings of Brazil's environmental defenders, were recently acquired by the Museum of Modern Art in New York City.

For this issue's Graphic Science column, along with writer Lori Youmshajekian, Fragapane, who is based in Turin, Italy, shows how climate events from droughts to hurricanes cascade to cause destruction far beyond their immediate impact. This interconnected web of consequences is vast, and there's no single, simple takeaway. "Oversimplifying these kinds of topics never helps" people understand them, she says. This story of compounding calamities "deserves to be told and visualized in its complexity."

Illustration by Mark Smith

RESIDENTIAL SPACE?

I was astounded by the challenges to leaving Earth detailed by Sarah Scoles in “Why We’ll Never Live in Space.” I could only conclude that we will never achieve this goal. But then I visualized someone witnessing the Wright Brothers’ first flight at Kitty Hawk, N.C., in 1903. That witness was probably amazed that this vehicle did get off the ground and fly a short distance. At that time it probably seemed incomprehensible that someday we would fly routinely across every ocean and mountain range and fly at supersonic speeds and at altitudes above 70,000 feet.

And it would have seemed even more unlikely that we would launch humans into Earth orbit and land them on the moon—and return them safely. These challenges surely seemed insurmountable, but they weren’t. Despite this well-documented article, I’m very hesitant to believe that we will never live in space.

TOM SCHUPPE *FOND DU LAC, WIS.*

We have been fed a steady diet of science fiction and fantasy for such a long time that many of us now think fantastic technology and achievements are right around the corner. Scoles’s article brings much needed skepticism and critical thinking to the subject.

KEN SHARPE *ATLANTA*

Scoles’s article on future space travel noted prolonged microgravity’s damaging effect on humans. I was put in mind of space-fiction stories of the 1950s in which astronauts lived in a giant rotating wheel. I am wondering if this idea is being considered for future space exploration. Such a wheel could be set to produce 1*g* of artificial gravity at the rim. Astronauts could live in such a space station in orbit around some planet of interest. There could be living accommodation plus working areas and offices situated in the rim, with further work areas with zero gravity at the hub. From such a space station, people could conduct robotic or possibly manned trips down to the planet surface. Most of the time they would be able to live in 1*g* and avoid the problems of prolonged weightlessness.

TREVOR WATERS *KENT, ENGLAND*

October 2023

SCOLES REPLIES: *Regarding Waters’s suggestion: The idea that humans could artificially create the feeling (and physiology) of Earth’s gravity in space by using a spinning spaceship goes back decades in science fiction—and in the minds and plans of nonfictional scientists. It’s indeed possible to simulate our terrestrial pull that way. But right now the size, cost and design of a ship or station that could re-create our planet’s gravity are prohibitive. Will that be the case forever? Maybe not.*

But whatever such a spacecraft might look like, it would not solve the small-gravity problem for places like Mars, where the lower g-force could continue to cause issues, and the solution would need to be different (even if it did involve spinning). When I spoke to scientists about the physiological difficulties of long-term space travel, “gravity” was a universal concern because we haven’t yet engineered our way out of the problem.

NO NOBELS

In “Nobel Oblige” [Observatory], Naomi Oreskes argues that crystallographer Rosalind Franklin should receive a posthumous Nobel Prize for her role in the discovery of DNA.

You can add another name to the list of women who got shafted out of recognition: the late neuroscientist Candace Pert, who discovered the brain’s opiate receptor. She was working in Solomon Snyder’s laboratory, so he got an Albert Lasker Basic Medical Research Award for the finding, and she got the snub.

CHARLES LARRY PEARCE *VIA E-MAIL*

While Oreskes makes a great case, it would be best to ignore such adulation as the Nobel Prize. It is the responsibility of magazines and newspapers to publicize inequality and inequities. There’s no need to amplify the role of some award as a barometer for true achievements.

VASU GANTI *BERKELEY, CALIF.*

GEOENGINEERING RISK

In “A Stratospheric Gamble,” Douglas Fox discusses proposals to put sulfur dioxide (SO_2) into the atmosphere to mitigate global warming caused by carbon dioxide. As the article notes, chemical reactions with SO_2 result in sulfuric acid (H_2SO_4). This can become acid rain, which kills the forests that take CO_2 from the atmosphere. The article made no mention of this potential unintended ecological consequence. There was great effort to stop sulfur pollution in the second half of the 20th century.

BUFF LEVINE *RENO, NEV.*

Fox provides an important review of the issues and likelihood of distributing sulfur dioxide into the stratosphere in an attempt to partially reflect solar radiation back into space to cool the planet (or portions of it) while humanity reduces emissions of heat-trapping gases.

“We have been fed a steady diet of science fiction and fantasy for such a long time that many of us now think fantastic technology and achievements are right around the corner.”
KEN SHARPE *ATLANTA*

Among some points in the article that, in my opinion, deserve more emphasis is the fact that the approach that is best-studied and closest to deployment would depend on developing aircraft that can fly in the thin air of the stratosphere to deliver the sulfur dioxide. The embodied energy for building a fleet of such specially engineered planes is almost certain to add to carbon emissions. So while preparing to undertake this feat of geoengineering, we will be making matters worse, increasing the odds of reaching one or more tipping points of climate chaos before we get started. And it seems improbable that we will develop fuels for these aircraft that will not also contribute to carbon emissions.
DAN HEMENWAY *MONTPELIER, VT.*

Engineering the skies really does seem like a huge gamble, with the prospect of many foreseen, and perhaps unforeseen, consequences. A safer alternative might be to launch a rocket to a Lagrange point between us and the sun, where a cloud of reflective dust could be released.
CHARLES GOODWIN
DUNEDIN, NEW ZEALAND

ERRATA
"Wine's True Origins," by Mark Fischetti and Francesco Franchi, incorrectly described the wines burgundy, rioja and barolo as varietals.

"Modernizing Nuclear Weapons Is Dangerous," by the Editors [Science Agenda; December 2023], should have said that the so-called nuclear sponging mapped in "Sacrifice Zones," by Sébastien Philippe, would kill up to several million from radiation exposure, not 90 million in the first two hours. The latter figure regards a 2019 estimate of the number of people killed within the first few hours of a nuclear war between Russia and the U.S.

In "The COVID Baby Bump," by Tanya Lewis and Amanda Montañez [Graphic Science; December 2023], the graphic representing "Mothers Born Outside the U.S." left out data for September 2020. The corrected illustration can be seen at https://www.scientificamerican.com/article/covid-caused-a-baby-bump-when-experts-expected-a-drop-heres-why

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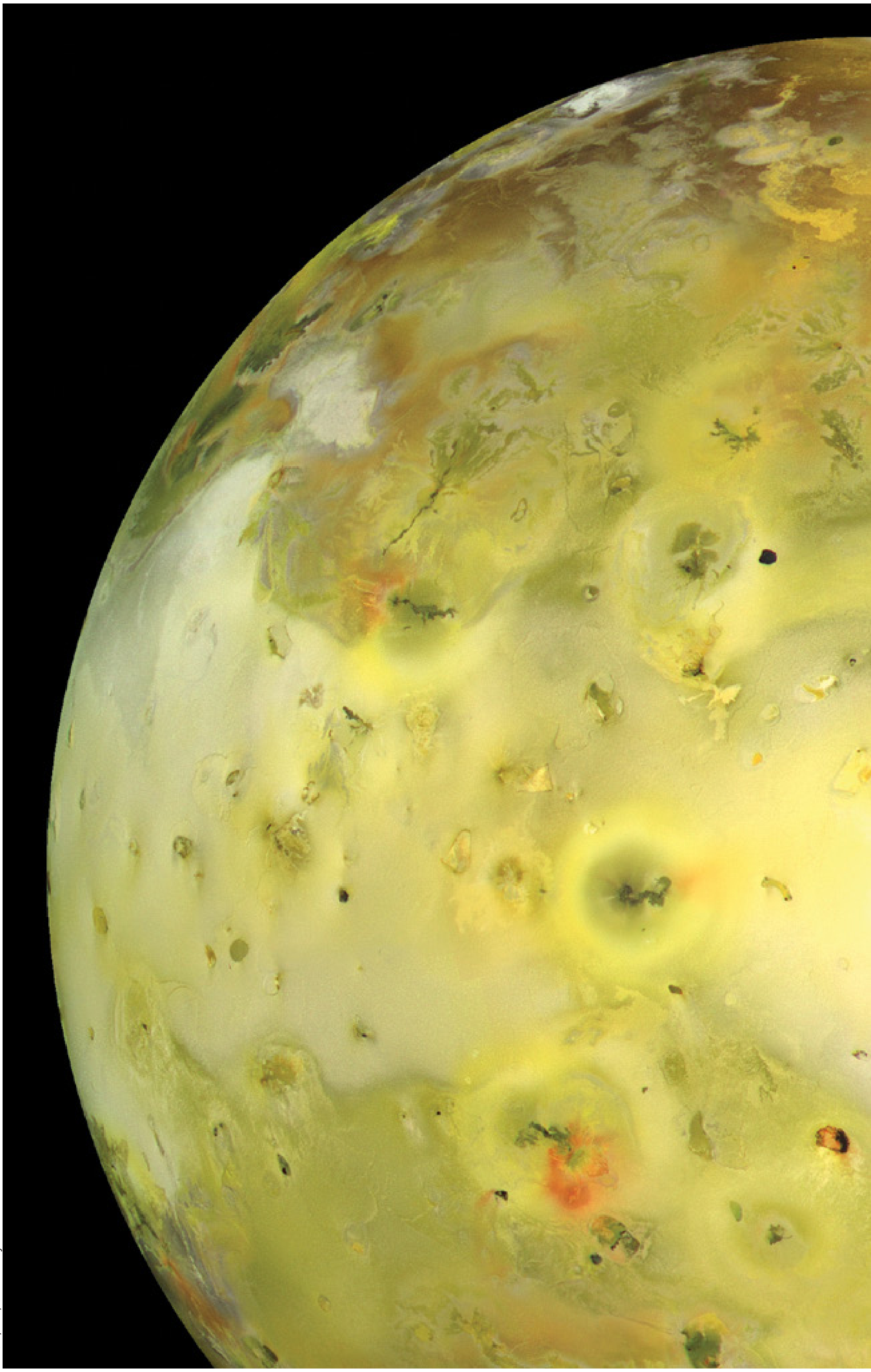
ADVANCES

SPACE

Erupting Moon

What heats the prodigious volcanoes on Jupiter's fiery moon Io?



NASA/JPL/University of Arizona

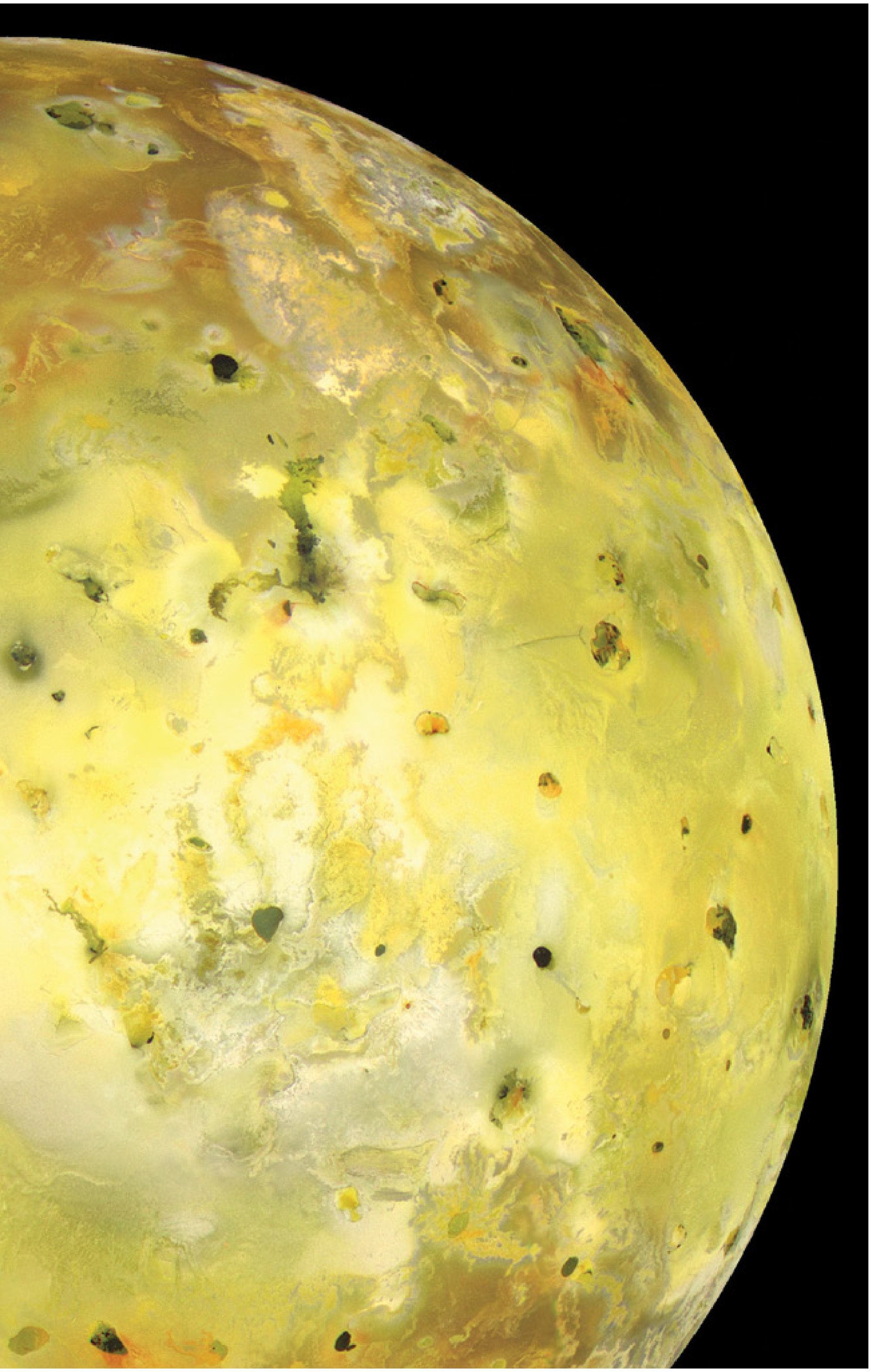
SCIENTISTS CAN SAY two things with certainty about Io. First, this moon of Jupiter is the most volcanic object in the known universe. Its surface is festooned with so many lava-spewing calderas that it resembles an oven-baked cheese pizza; its glowing rivers of molten rock stretch sinuously from horizon to horizon, and its endless eruptions spray towering arcs of matter into the vacuum of space.

Second, no one really knows the depth of this flashy orb's fiery plumbing. Are Io's volcanoes fed from reservoirs just underneath its crust, or does the heat well up from some far deeper source, near the moon's metallic core? Solving this mystery could also help reveal how Io's lunar sibling Europa and other icy moons manage to harbor vast, potentially habitable liquid-water oceans despite the outer solar system's sunlight-starved chill. Now the authors of a new study in *Nature Astronomy* think they have an answer: they're placing their bets on "heat engines" buried not too far below Io's surreal surface.

"Research like this provides invaluable insights into the diversity of volcanic activity and the interior heating of other worlds," says California Institute of Technology planetary scientist Anna Gülcher, who was not part of the new study. The work helps to winnow down researchers' models of where and how heat arises within otherwise frozen alien moons.

In a way, Io's internal heat can be traced to the presence of Europa and its other nearest neighboring moon, Ganymede: the two bend Io's orbit around Jupiter into an oval

COLOR WORDS SHOW A BILINGUAL BONUS P. 10
BACTERIA REMEMBER PAST SWARMS P. 14
DEEPWATER CORAL IN UNEXPECTED PERIL P. 16



that brings the hypervolcanic moon swooping closer to and then farther from the gas giant's wrenching gravitational grip. This movement raises tidal forces within Io that squeeze the moon's geological guts, generating enormous amounts of magma-making frictional heat. The question is where within Io that heating is concentrated—and, by proxy, where Europa's and other oceanic moons' tidal heating may originate as well.

Glimpses from NASA's Juno spacecraft have helped fill in views of Io's volcanic hotspots, letting scientists gather clues. These infrared images "are showing things nobody has ever seen before," says study co-author Ashley Davies, a volcanologist and planetary scientist at NASA's Jet Propulsion Laboratory. In particular, they reveal considerably more volcanic heat coming from Io's lower latitudes and equatorial expanses than from its comparatively lukewarm poles. This distribution suggests Io's tidal heating is concentrated not at great depths but higher up, closer to the crust.

"We have been wanting to have this data set for decades, and it's finally here," says Caltech planetary scientist Katherine de Kleer, who was not part of the new study. "The models [have differed] as to where the melting is mostly occurring—whether it's down at the core-mantle boundary or whether it's close to the surface."

Finding out which of these models works best demanded a global map of Io's erupting volcanoes. But existing maps remained incomplete, especially near Io's polar regions, because no spacecraft has been exclusively dedicated to investigating the moon.

Juno came to the rescue in 2016, when it entered a polar orbit of Jupiter. Taking advantage of this novel perspective, scientists used the spacecraft's Jovian Infrared Auroral Mapper (JIRAM) instrument—designed primarily to investigate Jupiter's magnetic field and polar auroras—to get a prolonged peek at Io's poles.

In the new study, the authors surveyed 266 volcanic hotspots across the moon. This map showed that Io's lower latitudes were emitting 60 percent more volcanic heat per unit area than the poles. The best explanation of this dichotomy is that Io's tidal heating is mostly happening at shallow depths, either within a puttylike upper mantle or within a partly or fully molten ocean of rock just below the crust.

"I'm kind of leaning toward a magma ocean," Davies says. But evidence is not clear-cut: the erupting volcanoes' positions don't perfectly match any heating hypothesis. "Io's going to be a lot more complicated," he adds.

The poles are also volcanically active, which implies that some tidal heating is occurring at greater depths. "There's probably some degree of melting happening everywhere," de Kleer says. Weirdly, the north pole is emitting more than twice the volcanic heat per unit area of Io's southernmost reaches. It's unclear why; Davies posits that a geological barrier below the south pole—perhaps a thicker crust or some other heat-resistant tectonic structure—inhibits the flow of hot rock to the surface.

Although these results may be the closest anyone can get to an x-ray of the ultravolcanic orb, they still contain huge uncertainties. Researchers cannot even be sure that the pattern of Io's volcanic thermal emissions is a reliable proxy for the moon's heat flow. "Magma will come to the surface where it can, even if that isn't directly over the melting source," says Tracy Gregg, a planetary volcanologist at the University at Buffalo, who was not part of the study.

And this map of Io's volcanic hotspots cannot be set in stone (molten or otherwise). Some volcanoes stay active for a long time, whereas others have short-lived paroxysms. Its ever-changing fiery face is "the delightful thing about Io," says Jani Radebaugh, a planetary geologist at Brigham Young University, who was not part of the study. "There is no way we can ever be done mapping all the volcanism."

Future pictures of the volcanic hotspots might look much different from this one, potentially supporting a different conclusion. For now, however, this thermal snapshot broadly aligns with past research. And as Juno continues its daring flybys, we will spy even more volcanic outbursts. "This is the purest form of discovery you can imagine," Davies says. "It's an absolute thrill to see these things." *—Robin George Andrews*

Thinking in Color
Becoming bilingual can change the way people think

PSYCHOLINGUISTICS Like the ancient Greek of Homer's time, the Tsimane' language has no set word for the parts of the color spectrum English speakers call "blue." Although Tsimane' does name a number of more subjective hues (think "aquamarine" or "mauve" in English), its speakers—the Tsimane' people of Bolivia—reliably agree on just three main color categories: blackish, reddish and whitish.

But bilingualism is reworking the Tsimane' tricolor rainbow, researchers recently reported in *Psychological Science*—offering a rare, real-time glimpse into how learning a second language can change how people think about abstract concepts and fuel language evolution. The data show Tsimane' speakers who also speak Spanish are borrowing the concepts of—but not the Spanish words for—new color categories such as blue, green and yellow.

"You could have imagined that they could have just started calling things *amarillo* and *azul*" (the Spanish words for yellow and blue), says lead author Saima Malik-Moraleda, a cognitive neuroscientist at Harvard University and the Massachusetts Institute of Technology. But instead "they're repurposing their own Tsimane' color words."

Malik-Moraleda and her colleagues asked 152 people who spoke Tsimane' or Spanish, or both, to name and sort a set of 84 differently colored chips. Bilingual participants sorted the colors into narrower categories in both languages. For example, to describe blue and green chips in Tsimane', they chose two hazy Tsimane' color terms, *yushñus* and *shandyes,* and repurposed them as distinct, consistent labels for their freshly acquired color concepts. But monolingual Tsimane' speakers used these words interchangeably for bluish and greenish colors.

These results add to the evidence that the languages we speak affect how we slice up the rainbow into color categories. The new study documented this effect in real time as a language evolved; other work in languages such as Greek and Welsh has relied on historical evidence to study this transition after the fact, says psycholinguist Panos Athanasopoulos of Lund University in Sweden. "What they're showing is the end process of this conceptual restructuring" associated with bilingualism, he says.

Although the results reflect changes in how bilingual people talk about the world, they do not reveal whether these speakers actually perceive colors differently than monolingual people do. Psycholinguistics evidence suggests the language we speak can subtly influence how our brains process what we see. Testing whether bilingual Tsimane' speakers' use of color terms reflects a difference in how they experience color—that is, whether their brains react to color differently than those of monolingual people—would be a fascinating follow-up, Athanasopoulos says.

"To me personally, I feel like it shows the beauty of language learning," Malik-Moraleda says. Even without borrowing words, it can "transform your own concepts in your native language." *—Elise Cutts*

Illustrations by Thomas Fuchs

EVOLUTION

Peak Evolution

Living fossils are constantly evolving

EVOLUTION CAN PERFORM spectacular makeovers: today's airborne songbirds descended from the wingless, earthbound dinosaurs that roamed millions of years ago, for example. But some organisms seem to change very little, even over eons—the coelacanth, a modern-day fish, is nearly identical to its 410-million-year-old fossilized counterparts.

Scientists have long wondered how these species withstand the pressures of natural selection. The prevailing hypothesis for this "stasis paradox" has been that natural selection keeps some species unchanged by selecting for moderate or average traits (so-called stabilizing selection) rather than selecting for more extreme traits that would cause a species to change (directional selection). But a study published in the *Proceedings of the National Academy of Sciences USA* contradicts this idea, showing that evolution constantly favors different traits in seemingly unchanging animals that improve short-term survival. In the long term, though, "all that evolution cancels out and leads to no change," says the study's lead author, James Stroud, a biologist at the Georgia Institute of Technology.

Stroud and his colleagues studied four anole lizard species, all relatively unchanged for 20 million years, living on a small island in Florida's Fairchild Tropical Botanic Garden. The researchers captured members of these populations every six months for three years. They measured each lizard's head size, leg length, mass and height, as well as the size of its sticky toe pads, noting which individuals survived. Stroud expected to observe stabilizing selection at work preserving moderate traits. Instead he saw clearer evidence of directional selection: some lizards with unique traits, such as stickier toes, survived better in the short term.

In each generation, though, the "best" traits changed—for instance, long legs aided survival in some years and short legs in others. The direction and strength of selection fluctuated so much that sometimes there was no clear pattern. Such changes are probably happening "back and forth on a micro scale with no net directional change," says Rosemary Grant, a Princeton University evolutionary biologist, who has studied stabilizing selection in Darwin's finches.

Because the new study shows that natural selection favored extreme traits from year to year rather than moderate ones, its results don't support the theory of stabilizing selection. Instead they offer "a good explanation for why we see what we think is stabilizing selection," says Tadashi Fukami, an ecologist studying evolution at Stanford University. Many new traits are evolving in the short term, but they don't provide a crucial advantage over the long term. In other words, species in stasis may simply have found the best possible combination of traits for lasting success in their environment.

So what happens when a static species' environment changes more dramatically? To help answer this bigger question, Stroud is still making trips to Florida to follow ever more generations of the lizards.

—Donavyn Coffey

Cuban brown anole

Paul Starosta/Getty Images

PUBLIC HEALTH

The Invisible Toll

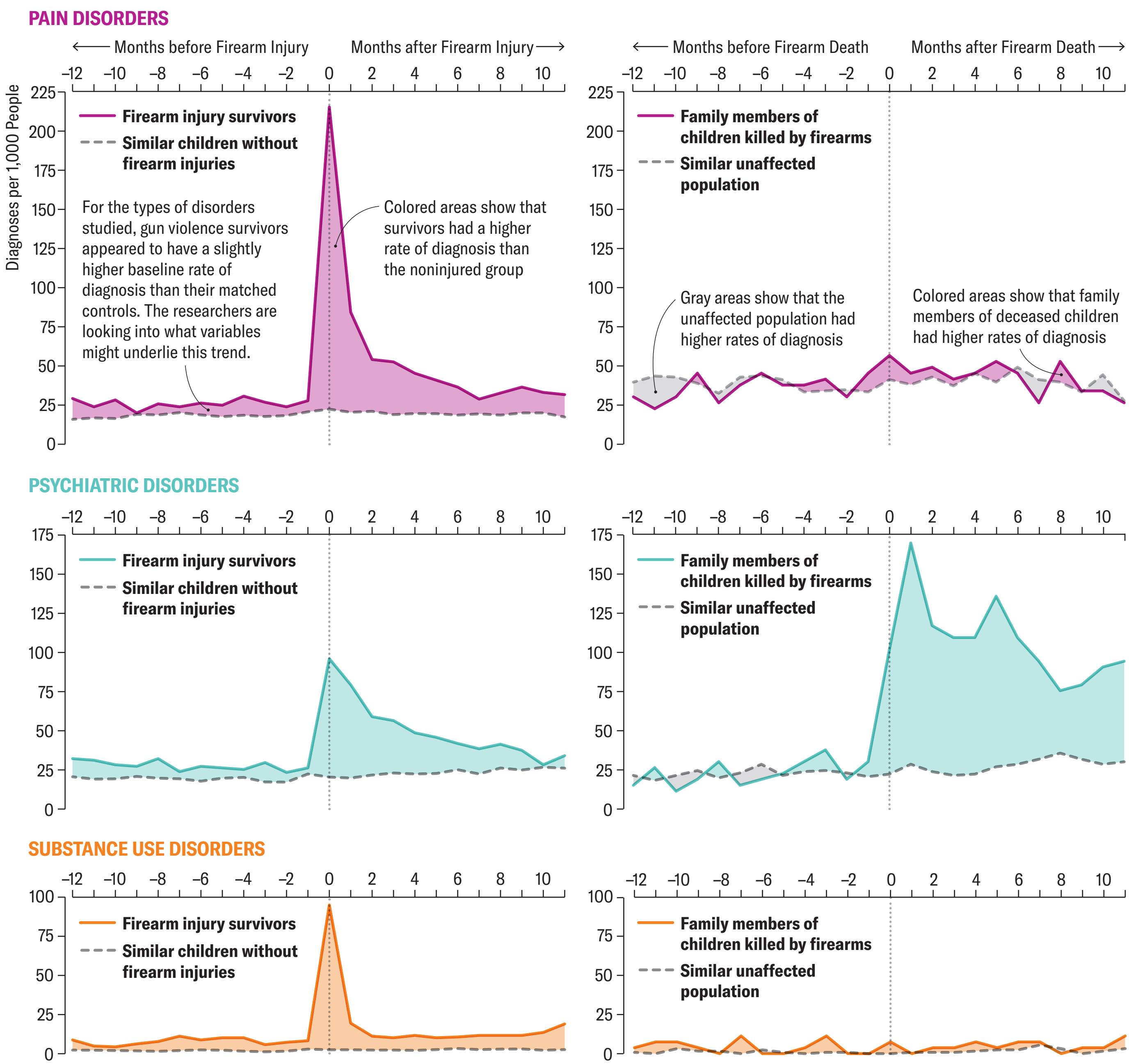
Mental health disorders spike in the aftermath of gun violence

FIREARMS HAVE BEEN the leading cause of death in the U.S. for people aged 19 and younger since 2020, killing more than 4,500 children and teenagers in 2022 and injuring many more. These statistics are just "the tip of the iceberg of the larger epidemic," says Zirui Song, who studies health-care policy and medicine at Harvard Medical School and Massachusetts General Hospital. In a recent analysis published in *Health Affairs*, Song and his colleagues quantify firearm injuries' often invisible ripple effects on the physical and mental health of children and their families.

"Survivors face a challenging, daunting, painful [and] often lonely road to recovery that receives very little attention," Song says.

How Firearm Injuries Affect Children's Health

How Firearm Deaths Affect Family Members' Health



Source: "Firearm Injuries in Children and Adolescents: Health and Economic Consequences among Survivors and Family Members," by Zirui Song et al., in *Health Affairs*, Vol. 42, No. 11; November 2023

Graphics by Amanda Montañez

Using data from employer health insurance claims filed between 2007 and 2021, the researchers compared more than 2,000 young survivors of gun violence with about 10,000 matched control subjects who had no firearm injuries. For survivors, the prevalence of substance use disorders and pain disorders more than doubled in the year following the shooting. Compared with the control group, after the shooting the survivors saw a 68 percent increase in psychiatric disorders such as post-traumatic stress disorder and major depressive disorder. The effects were worse for those with more severe injuries.

Survivors' parents were affected, too, experiencing a 30 percent increase in psychiatric conditions. "The whole family is a survivor of the firearm injury," Song says. Among parents whose children were killed by firearms, psychiatric diagnoses more than doubled.

This analysis captured data for just one year after a shooting, but the health effects of gunshot injuries can last a lifetime. "The journey of surviving is years, if not decades, long," says Lauren Magee of Indiana University–Purdue University Indianapolis, who is an expert on gun violence and its effects.

Shootings also take a financial toll. Health-care spending on survivors increased by an average of about $35,000 per person annually, which paid for mental health services, imaging, laboratory tests and home care, among other costs.

The analysis does not include those insured by Medicaid or Medicare or those without insurance. Some in these groups are at high risk of gun violence, as well as other physical and mental health conditions, because of their higher rates of poverty and limited access to health care, says Daniel Semenza, director of interpersonal violence research at the New Jersey Gun Violence Research Center at Rutgers University. In future analyses, Song and his colleagues plan to use government data to compare effects in more demographics.

Gun violence "shapes well-being across the entire population," Semenza says. "We have to take that seriously ... because we are at unacceptable levels of shootings—and we have been for many decades now."

—Lori Youmshajekian

Lifeline Decision

Premature babies significantly benefit from delayed umbilical cord cutting

MEDICINE When a baby is born prematurely, doctors often snip the umbilical cord and whisk the infant away for immediate medical intervention. But a new meta-analysis suggests they should not be so quick to sever the cord, which delivers oxygen and antibody-rich blood to the newborn.

To compare umbilical cord practices for preterm births, researchers collected raw data from dozens of randomized controlled trials involving nearly 10,000 premature babies from several countries. Their results, published in the *Lancet*, indicate that when doctors wait to clamp and cut the cord they reduce the risk of death for preemies, nearly one million of whom die annually worldwide.

In a companion study, the researchers found survival rates were best when doctors waited at least two minutes to clamp the cord—longer than most public health organizations currently recommend. "These are strong findings ... that longer is better," says Jessica Illuzzi, an expert on obstetric intervention at the Yale School of Medicine. "If you cut the cord too quickly, their heart is trying to pump, and there's just not enough blood."

Immediate cord clamping became commonplace only in the 20th century as childbirth practices moved from the home to the hospital. Over the past dozen years, however, research has increasingly shown that delayed cord clamping can boost a newborn's overall blood volume, red blood cell count and iron stores, as well as ease the transition to breathing. Many doctors now delay cord clamping.

Yet obstetricians often still balk at delayed clamping with premature babies, who are frequently born with visible health issues, says Anna Lene Seidler, a biostatistician at the University of Sydney and lead author on both studies. "They're sometimes not moving [or] breathing properly."

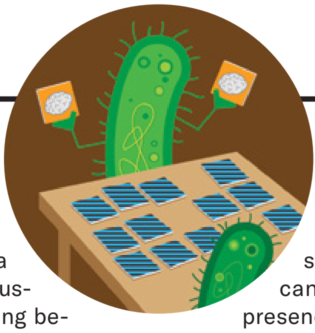
Some circumstances probably still warrant rapid clamping, such as when the mother is hemorrhaging or the infant needs immediate resuscitation. Yet as Seidler points out, much medical care, such as warming and stimulating babies, can be given with the cord intact. "We've come full circle," she says, adding that although modern medicine has vastly improved life for preemies, in this one respect the old ways were best all along. *—Jesse Greenspan*

kieferpix/Getty Images

Doctors or midwives choose when to cut a baby's umbilical cord after birth.

Microbial Memory

Bacteria swarm based on inherited experiences



MICROBIOLOGY Even organisms without brains can remember their past: Scientists found that Escherichia coli bacteria form their own kind of memories of exposure to nutrients. They pass these memories down to future generations, which can help them evade antibiotics, the research team reported in the *Proceedings of the National Academy of Sciences USA*.

"We typically think of microbes as single-celled organisms [that each] do their own thing," says Dartmouth College microbiologist George O'Toole, who studies bacterial structures called biofilms. In reality, bacteria frequently survive by working together. Much like honeybees relocating their hive, colonies of bacteria in search of permanent homes will often travel as collective units called swarms.

These swarms can better withstand antibiotic exposure because of their high cell density, making them of particular interest to microbiologists such as Souvik Bhattacharyya of the University of Texas at Austin. He was studying swarming behavior in *E. coli* when he observed what he calls "weird colony patterns" he had never seen before. By isolating individual bacteria, he and his colleagues discovered that the cells were behaving differently based on their past experience. Bacteria cells in colonies that had previously swarmed were more prone to swarm again than those that hadn't, and their offspring followed suit for at least four generations—about two hours.

By tweaking the *E. coli* genome, the scientists found that underlying this ability were two genes that together control the uptake and regulation of iron. Cells with low levels of this important bacterial nutrient seemed predisposed to form mobile swarms. The researchers suspect these swarms could then seek out new locations with ideal iron levels, Bhattacharyya says.

Past research has shown that some bacteria can remember and pass to their offspring details of their physical environment, such as the existence of a stable surface, O'Toole says, but this study suggests that bacteria can also remember nutrients' presence. Bacteria, some of which reproduce multiple times per hour, use these details to determine the longer-term suitability of a location and may even settle together in biofilms, which are more permanent.

Microbes other than *E. coli* probably remember iron exposure, too, O'Toole says. "I would be really shocked if [these results] didn't hold up in other bugs as well." He hopes that future research examines on a cellular level how bacteria translate iron detection into different behaviors.

Because bacteria are tougher to kill when they form larger structures, understanding why they do so might eventually lead to new approaches for addressing stubborn infections. This research provides an opportunity to develop new infection-fighting treatments, O'Toole says—especially crucial as antibiotics become less and less effective at killing these microbes.

—Allison Parshall

IMMUNOLOGY

Infant Power

What's behind babies' COVID-fighting prowess?

MANY INFECTIOUS DISEASES are deadly for both the very old and the very young. But thankfully, the COVID-causing SARS-CoV-2 virus rarely triggers serious illness in infants. Scientists have several theories as to why. For example, some evidence suggests babies' immature immune systems—which lack the more targeted (or "adaptive") responses that develop with age—mount a stronger first-line (or "innate") response against the virus.

Now researchers have profiled the entire immune system in young children to compare their response to SARS-CoV-2 with that of adults. The results, published in *Cell*, show that infants' systems mount a strong innate response in their noses, where the airborne virus usually enters the body. And unlike adults, babies don't exhibit widespread inflammatory signaling throughout their circulatory system, perhaps preventing severe COVID.

The research team, led by Stanford Medicine immunologist Bali Pulendran, took blood samples from 81 infants (54 of whom became infected with the virus between one month and three years of age) and dozens of adults. The researchers also took weekly nasal swabs from kids and adults with and without COVID. They then analyzed proteins and gene activity in these samples to track participants' innate and adaptive immune responses to the virus. "This sort of longitudinal mapping of the immune response of infants, to any virus, had not been done before," Pulendran says.

The team found stark differences between children and adults in both adaptive and innate immune responses. Infected infants' noses were flooded with inflammatory signaling molecules and cells. But unlike in the adults, there were no signs of inflammation in their blood. "There was this dichotomy between a raging war in these babies' noses and what's going on in the blood," Pulendran says.

"It suggests children have local control of the virus without systemic inflammation, and that's why we don't see severe disease [in them]," says pulmonologist Carmen Mikacenic of the Benaroya Research Institute in Seattle, who studies immune responses in the lungs.

Even without a widespread innate response, young children had surprisingly long-lasting levels of SARS-specific antibodies in their blood, Pulendran says. Future research revealing how these innate and adaptive responses are linked could eventually help improve nasally delivered vaccines for children and, potentially, adults.

A crucial question remains: What makes SARS-CoV-2 different from other respiratory viruses, such as influenza and respiratory syncytial virus, which *are* more deadly for infants? "If we can understand this protection in young children, could we harness it for other viruses they face?" asks Bria M. Coates, a pediatrician and assistant professor at Northwestern University's Feinberg School of Medicine, who studies kids' innate immune responses to flu and RSV. Pulendran and his colleagues are now conducting similar analyses for other viruses; that work is "very much ongoing," he says.

—Simon Makin

Serotine bat in flight

Mario Cea Sanchez/VWPics/Science Source

ANIMAL BEHAVIOR

Curious Copulation

Bats in a Dutch church demonstrate an unusual mating behavior

MOST MAMMALS MATE with penetrative sex, but new video evidence suggests that a peculiar bat species instead uses its oversize, bulbous penis like an arm to push away the female's tail membrane before pressing its tip against the vulva.

While collecting sperm samples from serotine bats (*Eptesicus serotinus*) several years ago, University of Lausanne evolutionary biologist Nicolas Fasel noticed that the species' erect penis was "huge"—about seven times longer and wider than the female's vagina—and had a large, heart-shaped tip. He and his colleagues puzzled over how penetration would be possible. Either the penis enlarges after penetration as it does in dogs, they reasoned, or the bats engage in contact mating, akin to how birds press their rear orifices (called cloacas) together to transfer sperm.

By chance, amateur bat enthusiast Jan Jeucken heard about Fasel's interest in bat reproduction and e-mailed the researcher videos he had taken of serotine bats mating in the attic of a church in the Netherlands. In the videos, there was clearly no penetration. Instead males used their penises to sweep aside obscuring tail membranes. The researchers theorized that hairs on the tip of the penis then helped to position it against the female's vulva before ejaculation. They included Jeucken as a co-author of their study, which was published recently in *Current Biology*.

"It was such an unusual type of behavior that we didn't really know occurs in mammals," says Teri Orr, a physiological ecologist at New Mexico State University, who studies bat reproduction. Orr says subsequent research should try to determine whether the sperm is being deposited during this observed behavior.

Although the new finding comes from a small sample of one bat species, "I have no doubt that this is more widespread," Fasel says. It seems likely that the behavior would occur among other bat species in which females have a similar tail membrane, Orr suggests. *E. serotinus*—which is common across Europe and Asia—and other bats are already known to have what Fasel calls "unique and quite peculiar" reproductive behaviors compared with other mammals. Many bat species can store sperm for months, and females can delay ovulation until after they hibernate. If this holds true for serotine bats, that might make it challenging for researchers studying their reproduction to link recorded mating events to later pregnancies, Orr notes.

Beyond the "gee-whiz" factor, these findings reveal important gaps in scientific knowledge about bat reproduction, Orr says: "Bats are such a poorly understood group, and they tend to be vilified. If we don't understand their reproductive biology, we're going to be really challenged when it comes to conservation."

—Lori Youmshajekian

OCEANOGRAPHY

Twilight Zone

Something is threatening these coral ecosystems

AS MARINE BIOLOGIST Nicola Foster and her colleagues steered a remote-controlled submersible through the coral reefs of the Indian Ocean's Chagos Archipelago, they saw corals full of color near the surface. But nearly 300 feet below, in the dimmer and colder waters of what oceanographers call the "twilight zone," some corals had turned ghostly white, leaving them vulnerable to disease and death.

"It wasn't something we were expecting to see," says Foster, who studies deeper-water coral ecosystems called mesophotic reefs at the University of Plymouth in England. Mesophotic reefs would seem to be buffered from rising sea-surface temperatures that blanch higher-up corals. But this team's 2019 observations, published recently in *Nature Communications*, show the deepest instance of bleaching ever recorded—suggesting similar reefs are more vulnerable than previously believed.

Bleaching often happens when warming water prompts corals to expel the colorful algae that live in their tissues and help to sustain them. Although surface waters weren't atypically warm when Foster and her team took their measurements, the twilight zone waters neared 84 degrees Fahrenheit (29 degrees Celsius)—far above the 68- to 75-degree range in which mesophotic corals thrive.

The researchers realized that bleaching corresponded with the timing of the Indian Ocean Dipole, a climate pattern similar to El Niño. This phenomenon shifts the region's surface winds and ocean currents, says study co-author Phil Hosegood, a physical oceanographer at the University of Plymouth. Wind and waves stir the upper ocean, keeping it relatively warm and uniform in temperature. But the 2019 dipole deepened this well-mixed upper layer; the thermocline (the slice of ocean that separates warm upper waters from the frigid depths) had plunged deeper than normal. "Those corals were exposed to temperatures that are normally found at the surface," Hosegood says. Researchers may have missed similar bleaching events in the past by not looking deep enough, he adds.

"This observation is really important," says Gonzalo Pérez-Rosales, who has studied similar ecosystems as a coral reef ecologist at the Woods Hole Oceanographic Institution, because it suggests mesophotic reefs elsewhere could also be bleaching. For instance, Hosegood says, El Niño may cause similar thermocline deepening in parts of the Pacific.

Fortunately, the corals in this study had largely recovered their color by 2022, Foster notes. But each bleaching stresses the corals and, if prolonged, can starve them. Another Indian Ocean Dipole event had already begun deepening the warm waters in this area by late fall of 2023, Hosegood says. He hopes future studies will reveal the physical processes behind where thermoclines deepen and how long this can last. Future Indian Ocean Dipole patterns are likely to be more severe, he says, noting that data suggest "that these natural cycles are becoming amplified with climate change." —*Carolyn Wilke*

Recovering corals at the Chagos Archipelago

University of Plymouth

SCIENCE IN IMAGES

Shimmying Schnoz

Elephantnose fish "sees" by doing an electric boogie

THE ELEPHANTNOSE FISH wouldn't get very far on eyesight alone in the murky rivers of western and central Africa that it calls home. Instead it relies on a sense called electrolocation: an organ on its tail emits a weak electric field that pulses outward from its body. Receptors on its skin detect distortions to the field caused by objects or creatures nearby, creating a two-dimensional "electric image" of the object being detected—like a shadow cast on the fish's skin.

But how does the foot-long fish use that 2-D map to perceive a 3-D world? New findings published in *Animal Behaviour* suggest this creature does a little aquatic dance, allowing it to perceive objects from slightly different angles that, when stacked together, help distinguish 3-D objects.

Sarah Skeels, an animal cognition and behavior researcher at the University of Oxford, has been thoroughly charmed by the elephantnose fish and its trunklike nose, technically called a schnauzenorgan (*below*), which is chock-full of electroreceptors. The fish is known for making odd movements, such as swiveling its schnauzenorgan or shaking its electrically charged tail, when it encounters unfamiliar objects. It sometimes even "moonwalks" with backward paddling that's very unusual in fish, Skeels says.

Skeels suspected these motions might help the elephantnose perceive its surroundings. To test the idea, she trained six Peters's elephantnose fish to associate a sausage-shaped block of aluminum with a reward of tasty bloodworms. Then she presented the fish with a choice of two objects behind mesh doors—one object shaped like a sausage, the other like a cube or sphere. After training, the fish quickly picked the door with the sausage shape almost 94 percent of the time.

Then Skeels began to shrink the space with mesh barriers so the fish had less room to shimmy, shake and throw it back. With a narrowed dance floor, the fish's accuracy dipped to 71 percent, and they took longer to reach a decision; there was "a level of hesitancy you don't see in the other trials," Skeels says.

The experiment was "very cleverly designed," says Stefan Mucha, who studies weakly electric fish at the Humboldt University of Berlin. He says it reveals a small but meaningful piece of how the fish integrate electrical information into a usable map, a complex process that has inspired underwater cameras and computer algorithms.

"It's so complex, what they do, that we can't really model it with our greatest computers," Mucha says. "But it's just a small fish!" —*Elizabeth Anne Brown*

Paul Starosta/Getty Images

NEWS AROUND THE WORLD

Quick Hits

By Lori Youmshajekian

THE BALKANS
Actions to reduce poisoning and electrocution from power lines have stabilized the endangered Egyptian Vulture's population in the Balkans. These birds are often killed across their 14-country migration route; only about 50 breeding pairs remain.

BRAZIL
Fossilized dinosaur footprints discovered in southern Brazil in the 1980s don't belong to any known species, new research shows. The desert-dwelling carnivore has been named *Farlowichnus rapidus* because its footsteps were spaced far apart, suggesting it was a speedy runner.

EUROPE
Ancient Europe's landscape was long believed to be a dense forest. But pollen samples from the interglacial period about 115,000 to 130,000 years ago have now revealed a mixture of grassland and light-woodland biomes, perhaps maintained by large herbivores such as elephants that trampled or fed on smaller trees.

GREENLAND
Glaciers in Greenland have receded twice as fast over the past two decades as they did in the 1900s—from seven or eight meters a year to about 15 annually. Archival images and recent satellite photographs showed the drastic acceleration.

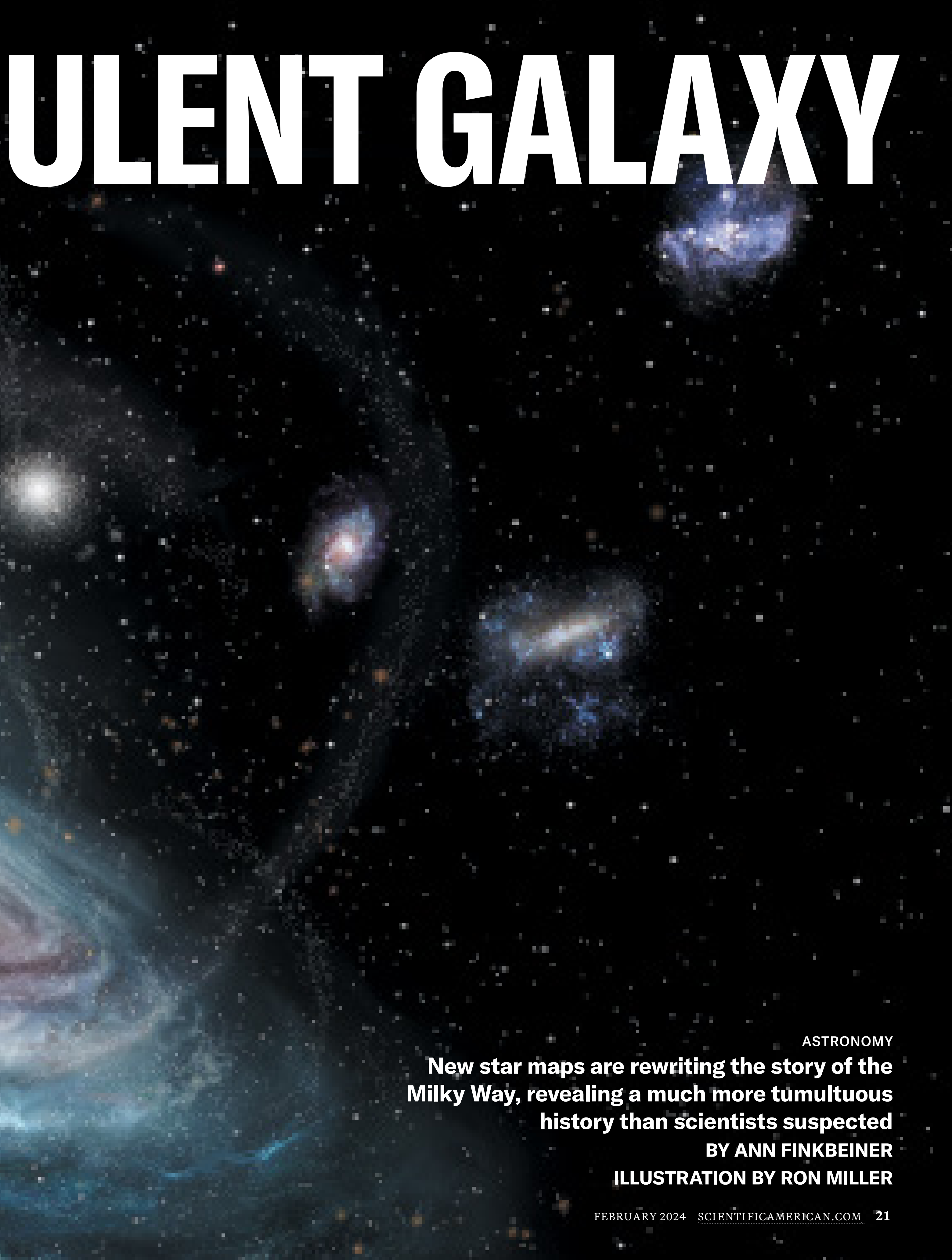
INDONESIA
Attenborough's long-beaked echidna, named for naturalist David Attenborough, was spotted for the first time since 1961 by trail cameras in the Cyclops Mountains. The spiky, egg-laying mammal had been scientifically recorded only once before; its timid and nocturnal nature makes it hard to find.

IVORY COAST
Researchers saw chimpanzees in Taï National Park climbing to higher ground to spy on neighboring rivals, mirroring a millennia-old human military strategy. The chimps also patrolled their borders to listen for enemies, and closer rivals were less likely to enter an adversary's territory.

For more details, visit www.ScientificAmerican.com/feb2024/advances

OUR TURB

ULENT GALAXY



ASTRONOMY

New star maps are rewriting the story of the Milky Way, revealing a much more tumultuous history than scientists suspected

BY ANN FINKBEINER

ILLUSTRATION BY RON MILLER

ASTRONOMER BOB BENJAMIN has spent the past 20 years trying to figure out what the Milky Way looks like. The work isn't easy, because we're inside the galaxy and can't see it from the outside, but astronomers have ingenious workarounds, and Benjamin thinks "it's a knowable thing." He carries in his mind a picture of what astronomers have been able to put together so far: a dense, barred center embedded in a layered disk of gas and stars, some of which pile up into arms that spiral through the disk, all encased in a sparse spherical halo of stars.

Piecing together this much of a Milky Way map has been so difficult that during interviews Benjamin and other astronomers repeatedly cite the story of the blind men and the elephant: men who cannot see each touch an elephant's trunk, ear or leg and respectively describe a snake, a fan or a tree trunk; they miss the whole elephant entirely. At least astronomers knew what they didn't know. They knew stars in different parts of the galaxy were different ages, but they couldn't account for why. They knew stars formed in gigantic clouds of gas, but the clouds were all but unmappable. They'd seen other galaxies merging with one another and looking unkempt, but they didn't know whether an earlier Milky Way might have done the same. When he began his career, Benjamin figured that the galaxy was in equilibrium, stable since birth, orderly and elegant.

But that picture has changed in recent years as scientists have begun systematically mapping stars wholesale. The bounty of data comes from a batch of new surveys, most notably one by the European Space Agency (ESA) observatory Gaia, that are collecting stupefying amounts of information. As of 1993, ESA's previous star-mapping satellite, Hipparcos, had mapped 2.5 million stars; by 2023 Gaia had mapped around 1.8 billion of them.

Gaia, which released its first data in 2016, has been complemented by an acronym soup of other telescopes and surveys—especially the Sloan Digital Sky Survey's (SDSS) Apache Point Observatory Galactic Evolution Experiment (APOGEE) and its just started Milky Way Mapper (MWM), as well as the Radial Velocity Experiment (RAVE), Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), GALactic Archaeology with HERMES (GALAH), Atacama Large Millimeter/submillimeter Array (ALMA), and Hectochelle in the Halo at High Resolution (H3). Collectively these projects have gathered images and spectra—stars' light spread out into its individual wavelengths—for millions of stars.

With all these data, astronomers are making the first exact maps of the Milky Way: locations of stars in three dimensions, plus a record of their motions made by repeatedly imaging them over time. The result is a deep, high-resolution movie of a few billion swirling stars that helps to reveal not only the galaxy's structure but also its surprisingly tumultuous history, along with the histories of its stars and the galaxy's means of making more stars. It's "the single largest increase in astronomical knowledge in, like, forever," says Charlie Conroy of Harvard University. "It's been shocking."

In short, the maps show not the Milky Way in static equilibrium, as researchers expected, but rather the galaxy's departure from it. As Benjamin, an astronomer at the University of Wisconsin–Whitewater, says, "Oh, my god, it's real. And oh, my god, it's a mess."

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

OF COURSE, MAPPING THE STARS is nothing new. Around 4,000 years ago ancient Mesopotamians watched the sun, moon and wandering planets move against the stars of the zodiac's constellations—the True Shepherd of Heaven, the Old Man, Pabilsag (a scorpionlike god), the Goat-Fish, the Hired Man—which they believed were laid out by the great god Marduk so people could arrange their lives and organize the year. If a baby was born in the month when the moon was in the Bull of Heaven, and the moon then moved night by night through the rest of the constellation creatures of the zodiac until it came full circle back to the bull, then the baby would be one month old. To track these motions, Mesopotamian astronomers looked at specific stars, which later scholarship called Normal stars, and held up fingers to measure the daily distances between the Normal stars and the moon, sun and planets.

By around 120 B.C.E. Greek astronomer Hipparchus had replaced fingers held against the sky with a universal grid of longitude and latitude on which stars could be located. Beginning in the early 1600s and continuing throughout the following, technologically remarkable centuries, astronomers invented telescopes, then bigger telescopes that could see fainter things. Then they added cameras and spectrographs that collected and dissected starlight, and later they refined the cameras' focus by flying satellites above Earth's distorting atmosphere. The technologies' outcome, like the number of stars, is also stupefying: The Mesopotamians might have been off by a finger or so held at arm's length, maybe a degree of arc, and Hipparchus was off by about half a degree, or 30 arc minutes. The Gaia satellite, however, is off by no more than 24 millionths of an arc second, the width of a human hair from 1,000 kilometers away. This kind of precision means astronomers can find structures in the Milky Way that are not only features of its map but also evidence of its history. Among the first structures found were confirmations of stars arcing through the halo in streams that were born together and still travel as one.

Ana Bonaca recently got her first faculty job, as a staff scientist at the Carnegie Observatories in Pasadena, Calif., but she's been interested in our galaxy since she was in middle school. She learned to use the floods of SDSS data to look for structures in the halo of stars that surrounds and is bound to the Milky Way. The halo, at the galaxy's farthest reaches, was known to be made of old stars and assumed to be featureless, but it is so dim that astronomers knew little else. "I was really drawn to the large-data-set, needle-in-a-haystack aspect" of the work, Bonaca says. In graduate school, her adviser suggested she look in the halo specifically for stellar streams. She didn't know what stellar streams were but soon decided that they were "pretty cool."

In 2006 first the SDSS and then other surveys began verifying halo stars with the same colors and brightnesses that seemed to move together in long streams, like one that Bonaca later worked on called Triangulum. Astronomers suspected the streams came from outside the galaxy—that their stars had been born together in some little, nearby galaxy. Then they were pulled into a stream when that galaxy came too close to the gravitational tides of the much larger Milky Way.

The maps show not the Milky Way in static equilibrium, as researchers expected, but rather the galaxy's departure from it.

This picture made sense, but verifying it was complicated. First, to believe that stars were in a stream, astronomers needed to see that the stars were related—that they'd been born in the same galaxy and were the same age. When stars are born together within the same gas cloud, they bear the distinct chemical signatures of the elements present in the cloud. As stars age, they turn light elements into heavier ones, which astronomers call "metals," then die in explosions that scatter the metals back into the gas around them. The more generations of stars that have lived and died in a galaxy's gas, the more metal-rich are the new stars born inside it; the more metal-rich, the younger the star. Stars in a stream, formed in gas clouds in the same galaxy, should have the same chemistry and ages.

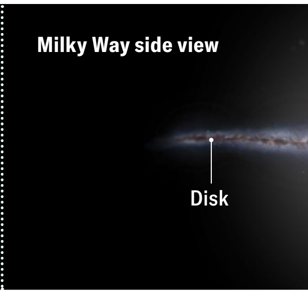
Second, stars in a stream should share the same motions. Motions toward or away from us are easy to calculate from stars' spectra, but measurements of their so-called proper motions across the sky have been imprecise. "If your error bars are too large, you can't see the stream," says Amina Helmi of the University of Groningen in the Netherlands, for whom the Helmi stream was named. "We were desperately waiting for Gaia."

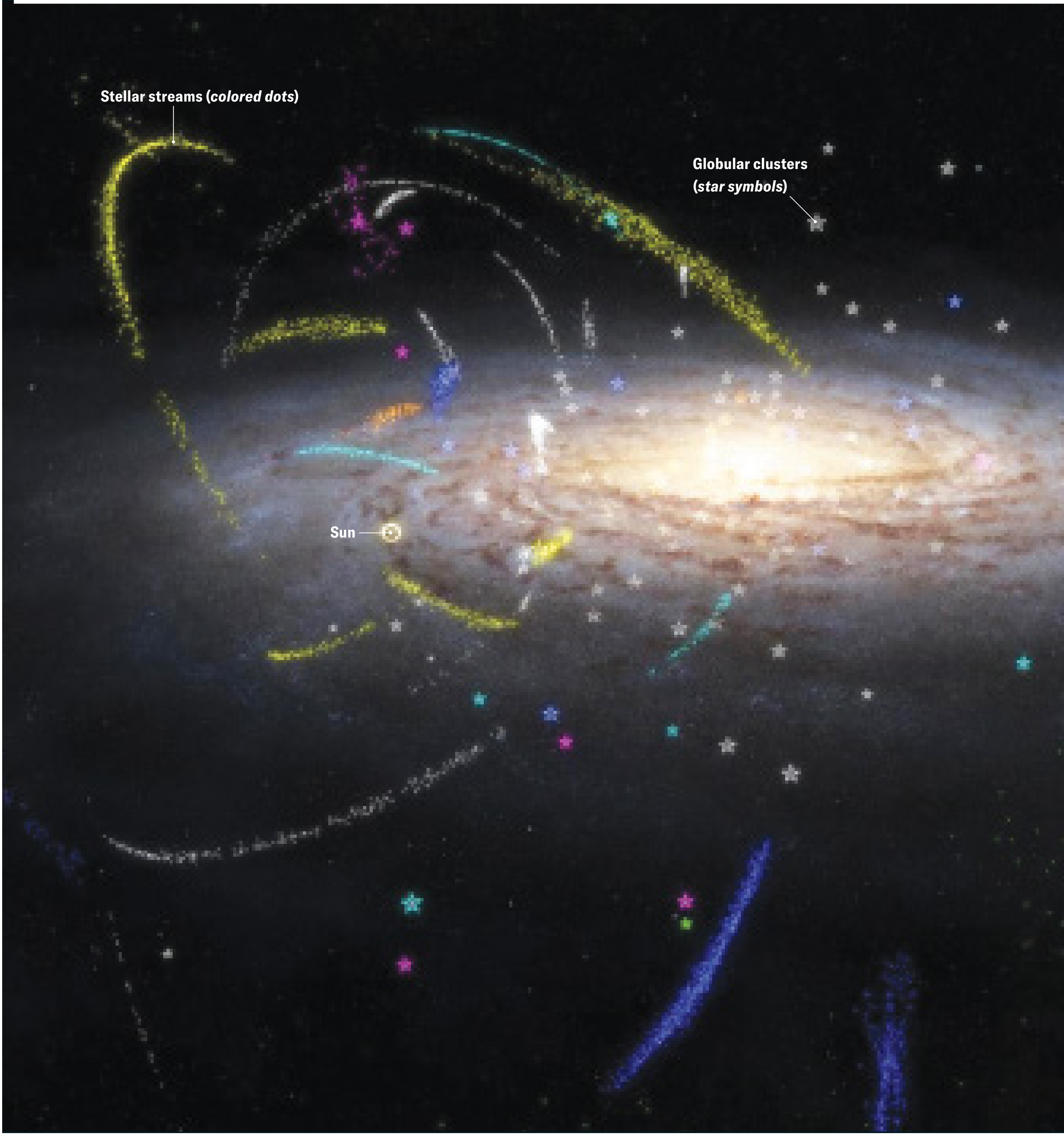
In 2016 Gaia began releasing its wealth of data—chemical compositions, ages, and precise three-dimensional locations and motions, including proper motions—for billions of stars. With Gaia data plus measurements from other surveys, notably SDSS's APOGEE, astronomers were able to reliably identify which stars were born outside the Milky Way and had immigrated in and which had been born here, "in situ." They could not only verify foreign star streams but also track each stream's orbit back to its own little galaxy.

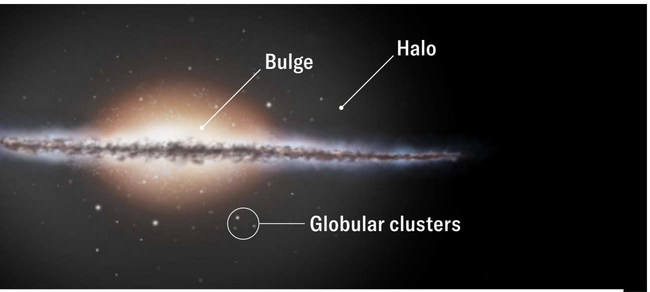
By 2021 astronomers had found 60 streams in the halo; 23 of them had likely birthplaces in dwarf galaxies or in the Milky Way's globular clusters (mysterious bound balls of up to a million stars that orbit our galaxy). Altogether, Bonaca says, there were "10 times more streams than before Gaia." The stars are generally around 10 billion years old. The ages of the

Atlas of the Milky Way

The Milky Way didn't form as a single, whole object; rather it built itself up in tumultuous stages over its 13-billion-year history. As other galaxies, dwarf galaxies and clumps of stars called globular clusters approached the Milky Way over the eons, they would merge with it. Sometimes their gas and stars integrated fully into ours, and other times our galaxy's stronger gravity would pull off streams of stars that would settle into the Milky Way's halo. The illustration below is based on an atlas of these mergers created by a group of astronomers led by Khyati Malhan of the Max Planck Institute for Astronomy in Heidelberg, Germany, using data from the European Space Agency's Gaia spacecraft.







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streams themselves are harder to estimate, but they are probably a few billion years old. Bonaca expects that astronomers will eventually find around 100 streams.

THE STREAMS RUNNING THROUGH the halo were some of the first signs of the galaxy's departure from stability. Then scientists began uncovering other groupings of stars that didn't follow expected patterns. In 2017 Bonaca and her team found a batch of Milky Way stars in the wrong place: they were in the old, metal-poor halo and had the orbits of old halo stars, but they had the metal-rich chemistry of younger stars from the Milky Way's disk. Bonaca wondered whether they were disk stars that had somehow wandered up into the halo.

The next year a team led by Vasily Belokurov of the University of Cambridge found an entirely different batch of stars in the halo that were going unusually fast and in the opposite direction from the rest of the halo. They named the wrong-way batch, which was bean-shaped, Sausage. A different team, led by Helmi, found that the bean's stars were also old and metal-poor; they called the bean Gaia-Enceladus, for the earth goddess Gaia's son, Enceladus. And in 2023 Bonaca and her colleagues found a stream of stars with the same old, metal-poor chemistry and wrong-way motion as the bean and thought this stream was probably tracing the bean's fall into the Milky Way. The astronomical community pragmatically settled on a compromise name for the bean, the Gaia-Enceladus Sausage (GES); the generic noun for a GES-type entity is "blob."

Meanwhile the Belokurov team had "rediscovered" Bonaca's team's misplaced disk stars, by now known to be part of the GES. In other words, in the midst of a foreign blob of metal-poor stars was a group of metal-rich stars native to the Milky Way. He and his colleagues suggested that when the GES collided with our galaxy, it splashed the native stars out of their normal orbits in the disk and up into the halo. They called the star group Splash.

Putting their blobs, streams and splashes together, astronomers concluded that between eight billion and 10 billion years ago, Enceladus—about a quarter of the size of the Milky Way—struck our galaxy head-on and merged into it as a blob. "Head-on, you smash in, fall apart fast and die," Belokurov says. GES stars now make up most of the Milky Way's halo, and the merger thickened its disk. Bonaca calls it "the most transformative event in Milky Way history."

Older, less violent transformations had happened not in the halo but in the body of the galaxy itself. In 2022 three different teams found signs of a protogalaxy apparently turning into a galaxy. Again, verification was complicated and hinged on knowing which stars were native to the Milky Way.

Harvard's Conroy was part of a team that measured the in situ stars' chemistry and found two populations: one group was ancient, metal-poor, moving chaotically and forming stars slowly; the other was

Illustration by Ron Miller (Milky Way side view)

With the new surveys' maps, we can see how the galaxy has warped and shifted with time and how it will continue to do so.

younger, metal-rich, moving coherently and forming stars 10 times faster. The astronomers thought the populations represented different stages of galactic history and called these stages "simmering" and "boiling," respectively. Meanwhile Belokurov and a team measured in situ stars' orbits and also found two epochs, he says: an early one with metal-poor stars' orbits going "all over the place" and a later one with stars richer in metals that were orbiting more coherently—"a transition," he says, "from hot mess to relatively cold spinning disk." They called the hot mess Aurora, after the ancient Greek goddess of dawn. Hans-Walter Rix of the Max Planck Institute for Astronomy in Heidelberg, Germany, and his team looked at the chemistry of two million in situ stars across the sky and found a gravitationally bound group of ancient, metal-poor stars in the center of the galaxy. They called it "the poor old heart" of the Milky Way.

Names aside, all three teams agree that they're probably studying the same transformation: a chaotic protogalaxy full of old, metal-poor stars going in no particular direction that then spun up into a disk and began to form new stars like fireworks. Bonaca, who was on Conroy's team, isn't sure the observations have converged into one consistent story, "but it does look like we're seeing some of the same things," she says. "It's a little like the elephant."

STARS TELL ONLY PART of the story because the Milky Way is only partly stars—the rest is mostly gas. Stars are born from gas clouds, so the two are intimately related. Nevertheless, astronomers who study stars and those who study gas work in largely nonoverlapping communities. Benjamin belongs in both but identifies more with the gas people than with the star people. Because stars are born in gas and later enrich that gas with the elements they produce, gas astronomers are interested in how the galaxy stays alive and therefore its present. And because stars retain the orbits and chemistry of their origins, star people tend to be interested in how the galaxy evolved and therefore its past. "I think of a galaxy as alive and breathing," Benjamin says, "and those [star] folks treat it like a crime scene that needs forensics."

Astronomers have been able to map gas clouds for only the past 100 years or so, because the clouds—which are large, diffuse and dim—are hard to study. Observers could outline their positions in the sky but could only approximate their distances and shapes. Gaia data allow scientists to detect gas clouds through their stars, but the method is indirect, done via a proxy of a proxy.

Gas clouds are 99 percent gas; the other 1 percent is dust, a fine soot mixed with the gas so thoroughly that a map of the dust is more or less a map of the gas. Dust can be identified by its effect on starlight: stars shining through dust look redder and dimmer. By mapping reddened, dimmed stars, scientists can trace an outline of the dust and therefore the gas. The dust-filled gas clouds are also peppered with well-known and precisely located stars, and astronomers can connect these stellar dots to map out the clouds. Still, a measurement this indirect, says João Alves of the University of Vienna, is like describing the elephant by "touching the hair on its tail" and looking at "one part in a million of the elephant."

A team of astronomers found a dozen or more long, threadlike clouds of gas, scattered like toothpicks throughout the galaxy's spiral arms, that might serve as birthplaces for the arms' wealth of new stars; the discoverers call the clouds "bones." Another team uncovered a single, much larger but similarly long and narrow gas cloud that it calls the Split. And a third group, led by Alves, mapped the gas clouds that had clusters of newborn stars—the "local stellar nurseries," Alves says. "The shock was that the nurseries are all aligned in a narrow line." Seen from the side, this alignment looks like a wave that, like the Split but larger, undulates through the plane of the galaxy; the researchers named it the Radcliffe Wave. The Radcliffe Wave is 10 times longer and 100 times wider than the bones.

One reason these filaments of gas are interesting is that they—the bones especially—probably coincide with the galaxy's spiral arms, and no one yet knows how many arms the galaxy has. So far the arms look less like coherent structures than like arms plus branching feathers, making a count of their number dicey. If we could look at our galaxy from the outside, we would probably see it as having something between the disorganized, blotchy arms of a so-called flocculent spiral and the elegant, orderly arms of a "grand design" spiral. The consensus: spiral arms are best studied in galaxies we don't live in.

More recently, another team mapped what is known as the Local Bubble, a nearly empty region around the solar system made of hot, rarefied gas, and found the bubble outlined by groups of young stars, all moving outward. The researchers proposed that the bubble was created about 14 million years ago when a cluster of stars exploded as supernovae, sweeping up ambient gas and carrying it into a large sphere on whose surface the gas cooled into clouds and began forming its own stars.

Benjamin and others wonder whether the gas structures—the bones, the Split, the Radcliffe Wave and the Local Bubble—are variants of the same thing: long filaments of gas inside which smaller clouds are compressed into stars. "You see this long, dark, [dusty] thing," Benjamin says, "and then, boom! There's a little bright bubble forming inside it, and then you see more dark line and then another bright bubble." It's "like pearls on a necklace," Alves says.

And maybe the Split, Radcliffe Wave and Local Bubble are historically related. The Local Bubble lies between the Split and the Radcliffe Wave. "We live in a bubble between a big snake and a smaller one," Alves says. He and his teammates speculate that if we could rewind time to see the locations and motions of the Split and the Radcliffe Wave 15 million years ago, we'd find that the two were close enough to intersect. Right at their presumed crossing point, where gas would have been densest and mostly likely to produce new stars, astronomers see a lively crowd of young stars in a group of clusters called the Scorpius-Centaurus association, Sco-Cen for short. Moreover, the Split-Wave intersection and Sco-Cen happen to be at the center of the Local Bubble and therefore arguably the bubble's origin. "But this is still not for sure," Alves says. "It just makes all the sense that [the intersection is] where the gas came from to form Sco-Cen."

IF THE STORY told by the stars is the galaxy's history of assembling itself, and if the story told by the gas is the galaxy's cycles of star formation, then the stars and gas together should show the galaxy's past and present, a movie that reveals what Benjamin calls "evolving disequilibrium."

Here is the elephant so far: Thirteen billion years ago, in a universe that was then less than a billion years old, the Milky Way was born as a shapeless cloud of gas and dust, forming metal-poor stars and rotating incoherently so that its stars' orbits were also haphazard. For the first billion or so years, smaller clouds and dwarf galaxies crashed into the baby Milky Way, sending up sprays of both immigrant and native stars into a halo. Gas carried by incoming colliders also set off more star formation in the Milky Way.

By about 12.5 billion years ago the galaxy was rotating more coherently; one billion to two billion years later it had spun up into a disk in which stars' orbits were tidily circular. Stars now formed at a quiet simmer, burned quickly through their lives and died explosively, enriching the gas out of which the next generations of increasingly metal-rich stars would be born.

Ten or so billion years ago the Enceladus galaxy collided with the Milky Way and, over the next two billion years, dissolved into it. The Gaia Enceladus Sausage took over the halo, sped up the stars in the Milky Way's thick disk and poured in gas, which, added to the Milky Way's gas, increased star formation. Gradually over the next two billion years inside the thick disk, gas and stars settled out into a denser, thin disk and collected into spiral arms.

Beginning around six billion years ago, a dwarf galaxy named Sagittarius sideswiped the Milky Way and swung around it. Every few hundred million years after that it brushed past the Milky Way again, each time "leaking stars in a trail," Belokurov says, creating streams that curved through the Milky Way's halo, wrapping around it twice. During the next five billion or so years, other incoming objects did the same until the entire Milky Way was surrounded with streamers. By then, in the spiral arms of the concentrated thin disk, gas had gathered into long threads—bones, waves, splits, filaments—along which stars lit up in clusters.

Closer to the sun, starting about 15 million years ago, massive stars in the Sco-Cen association formed, lived their fast lives and blew up, creating the Local Bubble, on whose dense surface more stars formed. The 37 clusters that now make the Sco-Cen association have fired off in bursts roughly every five million years, carving out more bubbles with more dense surfaces forming more stars, ensuring that the galactic neighborhood foams with new sparklers. The filamentary clouds don't survive the floods of radiation from star birth, and after five million to 20 million years they have "sheared apart" back into the galaxy, Benjamin says. There the gas will eventually cool and, under the influence of gravity and rotation, recondense into filaments and then again into stars.

And on planet Earth, maybe 4,000 years ago, a baby born in Mesopotamia grew up to know the names of the stars and constellations as though they were family or gods, to write them down in stone and use them to plant crops, measure time and predict lives. We've renamed the constellations since the god Marduk set them up: the Bull of Heaven is our Taurus; Scorpion is our Scorpio; Pabilsag is Sagittarius; and the True Shepherd of Heaven is now known as Orion. But we still use the constellations to locate ourselves in the galaxy, and we name its places, its clouds and streams, for earthly analogues.

With the new surveys' maps, we can see how constellations have warped and shifted with time and how the galaxy has and will continue to change. "We can run the movie forward and backward," Benjamin says. "We can do that with certainty."

The gas and star maps are complete near the sun but get hazy farther out. By 2023 astronomers had still mapped only about two billion of the Milky Way's 100 billion stars. "If the sun is my nose, we're still, like, here," says Alyssa Goodman of the Center for Astrophysics | Harvard & Smithsonian, touching her hands to either side of her face. "And the scale of the galaxy is, like, way out beyond the end of my arms. And so we're just trying to get, like, here, here, here." With each "here" she moves her hands farther and farther out until her arms are wide open, measuring the scale of the Milky Way with her human body, taking the galaxy as personally as any Mesopotamian baby. ●

FROM OUR ARCHIVES

New View of the Milky Way. Mark J. Reid and Xing-Wu Zheng; April 2020. ScientificAmerican.com/archive

PALEONTOLOGY

LOST WORLDS…

...OF THE DINOSAURS

Tiny fossils bring ancient ecosystems to life

BY KRISTINA A. CURRY ROGERS AND RAYMOND R. ROGERS

ILLUSTRATION BY SAM FALCONER

ENTER THE FOSSIL GALLERY of a natural history museum, and you're likely to encounter spectacular skeletons of some of the most manifestly awesome creatures ever to have walked our planet: dinosaurs. From towering sauropods and fearsome tyrannosaurs to tanklike ankylosaurs and horned ceratopsians, dinosaurs dominate our conceptions of the past. But to understand these animals and their world, scientists must look beyond the dazzling remains of *Apatosaurus, Tyrannosaurus,* and other icons to tiny fossils that appear, at first glance, distinctly unimpressive. You won't see these humble microfossils on public display, but they provide some of the best clues we have into the lives and times of our favorite prehistoric beasts.

For the past three decades we have been conducting expeditions to recover such fossils in the Upper Missouri River Breaks National Monument, a 149-mile expanse of astoundingly beautiful badlands in central Montana. Here in the very place where scientists got their first look at North America's dinosaurs starting in the 1800s, our team has discovered a wealth of fossils from an extraordinary array of previously unknown organisms that lived alongside those better-known dinosaurs. These fossils are a record of an ecosystem that flourished 10 million years before a killer asteroid slammed into Earth.

We have been targeting special fossil assemblages called vertebrate microfossil bonebeds, or VMBs. These sites preserve thousands of small, hard parts of a diversity of animals, ranging from traces of microscopic parasites, to the scales of minnows, to bits of much bigger frogs, turtles, birds, mammals, crocodiles and dinosaurs. We find the fossils both in the field and in the laboratory, where we use dissecting microscopes to search through sediment for the minuscule remains. These well-preserved fossils are providing some of the highest-resolution pictures yet of a dinosaur ecosystem. They reveal the often overlooked creatures that scurried and swam around the feet of dinosaurs, buzzed annoyingly in their ears and maybe even preyed on their young—and scavenged their dead. With them in the mix, the ancient world springs to life.

Kristina A. Curry Rogers is a professor of biology and geology at Macalester College. She studies the biology of dinosaurs, especially their growth rates and the anatomy and evolution of titanosaurs, the latest-surviving lineage of the long-necked sauropods.

Raymond R. Rogers is a professor of geology at Macalester College. His research focuses on ancient sedimentary environments and vertebrate taphonomy—a field of inquiry that explores how organisms become preserved in the fossil record.

THE TWO OF US bring very different perspectives to studying VMBs. Kristi works to understand the biology of the biggest dinosaurs of all time—the long-necked, quadrupedal plant eaters called sauropods. These giants have captivated her for as long as she can remember. Kristi has been happiest toiling in a sun-drenched quarry, slowly excavating limb bones far bigger than she is. Ray, in contrast, is a geologist who works in the rocks to decipher how bonebeds—accumulations of skeletons—form and what they reveal about the environments of an organism's life and death. Luckily for us, in addition to being married, we are each other's closest scientific collaborators.

Long before we joined forces, Ray had been busy working in fossil deposits that were the antithesis of the ones Kristi was focused on. Rather than spending an entire field season excavating a single enormous skeleton, Ray might collect thousands of fossils in a few hours in the VMBs. This achievement sounds amazing, but most of the fossils from the VMBs are so small that you could sneeze and blow them off your fingertips. With her enduring love of digging up the biggest of the big, Kristi was a reluctant convert to the study of VMBs. But looking at the tiny remains with handheld lenses and microscopes revealed perfectly preserved bones of a menagerie of creatures that lived in the shadows of her giants. Microfossils from the VMBs, Kristi realized, have outsized power when it comes to exposing the workings of dinosaur ecosystems.

The sun sets in the Missouri Breaks. The rock beds of the Judith River Formation, exposed on both sides of the valley, contain special assemblages of tiny fossils.

Jeff Thole

Through our work in the Upper Missouri River Breaks National Monument—or the Breaks, as it is known—we've been able to reconstruct one such ecosystem in remarkable detail. It's a scene many decades in the making. In 1855 a 26-year-old explorer and naturalist named Ferdinand Hayden was the first to investigate the Breaks geologically. For a few short days he traversed the roughly 76-million-year-old outcrops there. His foray into these fossil-rich rocks yielded the first scientific collection of dinosaur bones and teeth discovered in all of North America. But Hayden didn't just collect dinosaur remains. From what we would now recognize as a classic VMB, he also picked up a handful of bones and teeth from fish, turtles and crocodiles. With his first major find, Hayden not only populated our view of prehistoric North America with a bunch of dinosaurs but also began to reveal an ancient ecosystem.

For more than 30 years we, along with our gangs of undergraduate students, have followed in Hayden's footsteps. We do it old school, canoeing and hiking through the badlands and braving the heat, mud, bugs and snakes as we search for remnants of animals that lived in the Cretaceous period. Our work has produced tens of thousands of bones and teeth of dinosaurs and the animals that lived alongside them. We've learned how these special fossil assemblages form, which creatures these fossils represent and some of what they can teach us about the complex Cretaceous world that dinosaurs made famous.

AT THE HEART of the Breaks lies the Missouri River, the landscape architect responsible for carving the dramatic "break" in the undulating plains that gives the area its name. Rocky exposures soar many hundreds of feet above the river valley. These striated layers of sandstone, mudstone and coal make up the Judith River Formation.

Marine sandstones and shales found near the bottom and top of the formation indicate that the sea was never far away in the Cretaceous. Back then, Judith River sediments were accumulating near the coastline of a shallow inland sea known as the Western Interior Seaway. The seaway, which stretched from the Arctic Ocean to the Gulf of Mexico and east through what is now Hudson Bay, essentially divided North America into three parts. In the Cretaceous, the sea's shoreline was just a few miles to the east of where we work now, making our field area in the Breaks beachfront property. Ancient rivers flowed from the nascent Rocky Mountains toward the Western Interior Seaway. Swampy floodplains surrounded these Cretaceous rivers; it was an environment analogous to Louisiana's Atchafalaya Basin or the Florida Everglades.

Such places offer the perfect conditions for producing an exceptional fossil record. Warm, wet environments have an abundance of food and water that can support many different plants and animals. When these organisms died in what is now the Breaks, their remains accumulated slowly and steadily in the quiet lakes and wetlands, eventually getting covered in fine-grained mud. The sediment chemistry in these swampy systems is similarly favorable to long-term preservation. Instead of dissolving delicate bones, teeth and shells, the chemical conditions promoted fossilization, basically transforming these body parts into stone.

Geological forces have also played a part

To reach their fossil-hunting grounds in the Breaks, the researchers paddle 50 miles down the Missouri River.

Jeff Thole

in preserving these organisms for posterity. The entire region was tectonically active, part of a huge geological basin that formed as nearby rising mountains pushed down on Earth's crust. This basin allowed the Judith River Formation sediments and the fossils they preserved to accumulate instead of being eroded away into the sea. The erosion that this region is now experiencing makes it possible for us to find the fossils in the rocks.

Although parts of the Judith River Formation preserve big, beautiful dinosaur skeletons, the areas we target, deep within the river valley, are a little different. These sites—the VMBs—preserve a multitude of bones, teeth and other bits just a fraction of an inch in size from organisms ranging from dinosaurs to mollusks.

Scholars have long debated how VMBs form. One of the first hypotheses suggested that the fossils preserved in VMBs had collectively passed through the digestive tracts of ancient carnivores and that the sites represent concentrations of feces. Although scatological assemblages do exist in the fossil record, this explanation cannot, on its own, account for the quality of preservation and the geological context of the Judith River VMBs. Another hypothesis held that VMBs form when the flow of a river picks up and carries small, hard parts from an array of animals and deposits them in a single spot. But the geological and forensic data we have collected in the Judith River Formation are largely inconsistent with this transport-based scenario.

Along with our collaborator Matthew Carrano, dinosaur curator at the Smithsonian Institution's National Museum of Natural History, we've spent lots of time dissecting the fine-scale details of more than 20 Judith River Formation VMBs and developed a new model for how these sites develop. Our data indicate that these VMBs accumulated within ponds and lakes. Fine-grained sediments rained down on the remains of animals that lived and died in and around these long-lived aquatic ecosystems. Over time tough skeletal remains collected on the bottom and formed fossil deposits. As bottom-dwelling organisms burrowed through the mud, scavenged carcasses and churned up sediments in the course of their daily routines, individual skeletons broke, and their elements dispersed.

This scenario explains why VMBs yield skeletal fragments that are generally disarticulated and why the body parts that persist tend to be particularly durable and robust (think teeth, small bones and scales). When you study VMBs, you can't connect a thigh bone to a knee bone like you can when you find a lone dinosaur skeleton. But VMBs tell us much more than a single large skeleton can because they preserve communities.

WHERE THE PAVEMENT ENDS ... the Fun Begins." That's the slogan printed on the beer koozies at our local bar in the town of Winifred, Mont., population 200, more or less. There is no better description of this little prairie oasis. Winifred is the last stop in civilization before we leave the pavement for dirt tracks and river currents. We're headed to an area where few people travel, which is just the way we like it. For us, as it was for Hayden, the best ways to get to the farthest and most interesting reaches of the Breaks are by boat and on foot.

Once we leave the pavement behind in Winifred, the tracks wind down to the river, where the heat radiates off the rock walls of the valley—it's usually at least 10 degrees hotter on the river than it is up in Winifred. The air is still, and the Breaks are silent apart from the occasional clacking and snapping of wings as grasshoppers launch themselves skyward.

Only a few roads cut through this territory. One of them leads to Stafford-McClelland Ferry terminal, where overhead cables guide a platform ferry across the Missouri River. It's one of the only places to cross the river for miles, and it often serves as the launch point for our flotilla of canoes. Once we start our journey, chances are slim that we'll see any other humans until we go ashore farther downstream. We're loaded to the gunwales with the gear we'll need for a 50-mile paddle, including as much water as we can carry, all our food, tents, and collecting supplies, including several five-gallon buckets, mostly for collecting fossil-bearing sediment (at least one will serve as our toilet for the next several days). The only running water on our journey will be the silty river. Baths will be dunks that require wading through sticky, knee-deep mud. They cool us off, but we usually end up dirtier than before.

The badlands hug the river around us, creating a corridor of rock with nothing but sky overhead. Bald Eagles nest in stands of cottonwoods that line the banks, and Osprey scan the river ahead of us in search of a meal. Beavers surface and slap their tails in warning, the sound echoing off the hillsides and reverberating downstream. Every now and then we can discern the silhouettes of huge catfish and carp just under the murky surface, and occasionally a soft-shelled turtle pokes its pointed head up midriver to check us out.

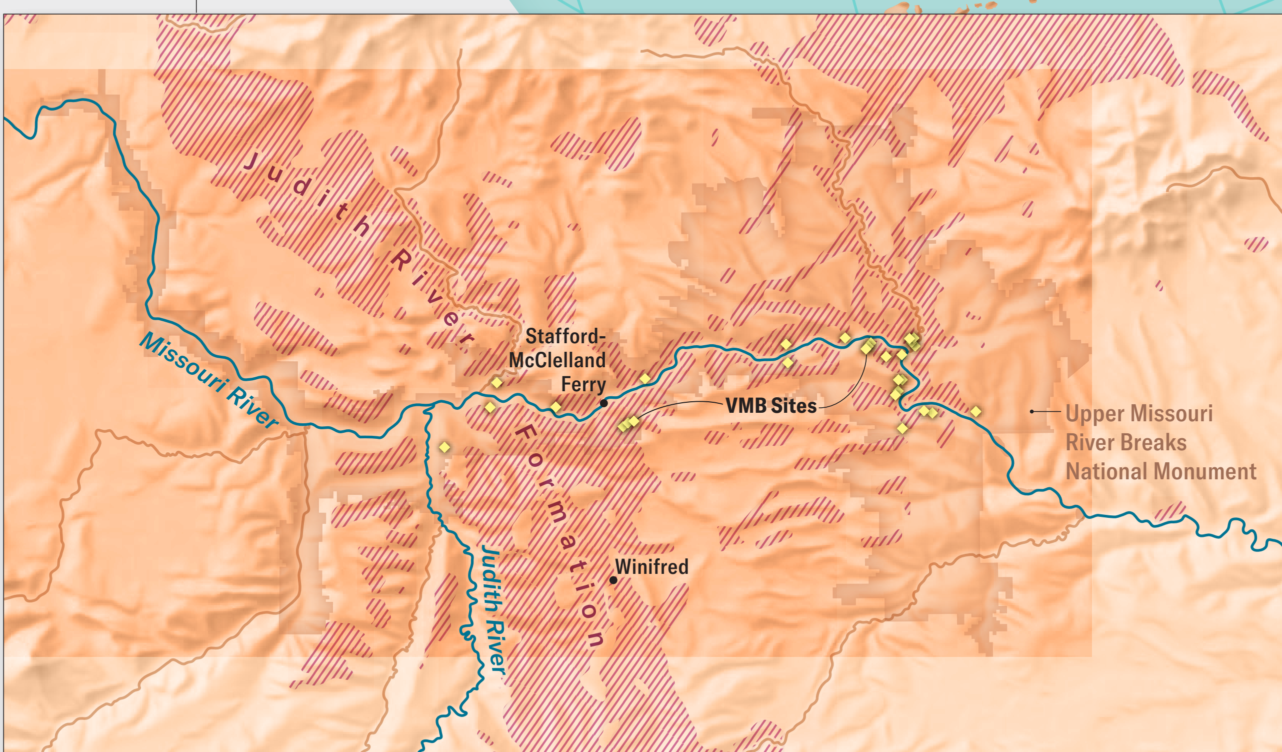
In the afternoon stillness, the sun beats down, heating our aluminum canoes and our shoulders. We stick our feet overboard to cool down. We swat away mosquitoes and no-see-ums, gnats that love to bite ears, eyelids and hairlines. If the wind is up, we might tie the canoes to one another with bungee cords and raft together, holding up a tarp as a makeshift sail and speeding away downstream. Late in the after-

On the Shores of an Ancient Inland Sea

Back in the Cretaceous period, a shallow inland sea known as the Western Interior Seaway divided North America into three parts. Rivers flowed from the incipient Rocky Mountains toward the seaway and were surrounded by swampy floodplains—conditions that promoted fossilization. The authors search for concentrations of small fossils called vertebrate microfossil bonebeds, or VMBs, in the layers of sediment that accumulated near the coastline of the ancient seaway. Over the years they have found 28 VMBs in the sedimentary rocks of the Judith River Formation in the heart of the Breaks.

LATE CRETACEOUS
(75 million–76 million years ago)

TODAY



Source: "PALEOMAP Paleodigital Elevation Models (PaleoDEMS) for the Phanerozoic," by Christopher R. Scotese and Nicky M. Wright. Zenodo, 2018, https://doi.org/10.5281/zenodo.5460860 (*paleo map data*)

Maps by Daniel P. Huffman

noon we'll find a spot in the welcoming shade of the cottonwoods and set up camp.

We wake with the sun and hike out into the hills, looking out for rattlers as we dodge spiky yucca and cactus and weave our way through stands of aromatic sagebrush. We occasionally spook a bighorn sheep resting in the shadows or get spooked ourselves as another sheep trots along the highest cliffs above us. Our eyes are trained on the ground and nearby slopes as we prospect for VMBs.

It might seem impossible to find such small fossils in this vast landscape, but there are a few clues to guide us. We search for just the right kind of sedimentary rock: dark gray and brown mudstone, maybe with some coal-black fossilized plants that indicate a swampy environment, and lighter gray sandstones bearing angled patterns that reflect ancient currents. We also look for exposures that sparkle in the sun. The sparkle comes from fragments of fossilized clams and snails that lived and died in Cretaceous ponds and lakes. VMBs are often found within these glittering layers of rock.

When someone spots a few broken fragments of fossils that have weathered out from a rock layer somewhere upslope, we'll track those bits and pieces back to their source, slowly crawling up the incline on our hands and knees, noses to the ground, eyes scanning for the tiny fossils emerging from the eroding rocks. Eventually we'll hit the layer where the fossils are concentrated. We can spend an entire day or more on a single small hill, using an ice pick or a pocketknife to help gently nudge fossils from the soft rock of the VMB. We collect everything that we can see, carefully adding our fossils to sample bags and vials. After we've scoured the surface, it's time to bring in the rock hammers, hoe picks and shovels. We excavate blocks of the bonebed and load them into our five-gallon buckets and giant sample bags.

Once we're back at our college lab, we load the fossil-bearing sediment into a contraption we call "the Dunker." This automated device washes the bonebed sediment through stacked sieves with different mesh sizes. We place the sediment chunks into one sieve that captures any fossils and bits of rock larger than about 0.08 inch in size but allows smaller pieces through. Below this sieve is a fine-mesh sieve that captures fossil bits down to 0.02 inch in size (smaller than a pinhead). After a few hours in the Dunker, most sediment clumps break down, and the sediment washes away, leaving behind a residue of bones, teeth, shells and other fossils in the sieves.

With the fossils recovered, we move to microscopes. Our students have spent hundreds of hours focusing on the fossils retrieved after sieving. They use superfine paintbrushes with bristles thinned to just a few hairs to sort through the fossil concentrates. It is remarkable what the VMB world looks like under magnification. What the naked eye perceives as mere specks of black resolves into perfect little teeth, jaws, limb bones and vertebrae. The diversity of the Judith River Formation comes to life.

LET US INTRODUCE YOU to the cast of characters we have met in the VMBs. We begin in the terrestrial realm, where the stars of the Cretaceous, the dinosaurs, lived. Dinosaurs had teeth that were replaced throughout life, and these teeth are some of the most common and easily identified fossils in our collections. Some of the dinosaur teeth in our VMBs belong to armored ankylosaurs such as those in the *Zuul* genus and dome-headed pachycephalosaurs such as *Stegoceras.* By far the most abundant dinosaur teeth in our samples come from herbivorous dinosaurs with rows of teeth that formed a grinding surface functionally similar to the molars of mammals. Usually we find only ground-down fragments of these teeth, so identifying particular species can be tough, but we've recovered teeth from duck-billed hadrosaurian dinosaurs, including *Brachylophosaurus,* and from horned and frilled ceratopsians, such as *Spiclypeus.*

Our sites have also yielded traces of carnivorous dinosaurs, which were the top predators in this Late Cretaceous ecosystem. Sharp, serrated teeth document the presence of *Tyrannosaurus rex* cousin *Daspletosaurus* and the small, feathered theropod *Troodon.* We've also found claws and vertebrae from the toothless, ostrich-like theropod *Ornithomimus.* Dinosaurs ruled the skies of the Judith River ecosystem, too, in the form of birds. Small, fragile animals typically don't get preserved very well, but many early birds had teeth, which are durable enough to survive in VMBs.

Like birds, mammals are another elusive group in the Late Cretaceous fossil record. But we know they made their way to the Judith River Formation lakes and ponds because we occasionally find teeth from little furballs such as *Alphadon,* which was similar to living opossums.

These mammals may have fallen prey to some of the many aquatic reptiles that lived in and around the ancient lakes here. Crocodiles and alligators, big and small, hunted the open waters and the shorelines. Their teeth, vertebrae and bony plates of armor are among the most common VMB fossils. One unusual creature in the lineup is *Champsosaurus.* This long-snouted, sharp-toothed animal looked somewhat like today's gharial, a fish-eating crocodilian that ambushes its prey. The spool-like vertebrae and broad ribs of *Champsosaurus* turn up frequently at our sites, signaling that it was a prominent player in the Judith River Formation ecosystem.

As you might expect in this 76-million-year-old water world, fish were abundant. Our collections include thousands of vertebrae, teeth and scales representing both large fish and minnows. These fish would have schooled in the Judith River Formation lakes, making the water shimmer with their collective movement. Freshwater sharks also swam in these waters, as did *Myledaphus,* a guitarfishlike creature with flat, diamond-shaped teeth perfect for crushing small crustaceans and mollusks.

Ferocious gar fish (*Lepisosteus*) were also numerous. Their scales help us document a fascinating story of ecological interaction among species in the Judith River Formation. The bodies of gars are protected by an armor of interlocking scales covered in a special type of enamel-like tissue called ganoine. When crocodiles ingest gars, the acids in their harsh digestive systems strip away the outer layer of ganoine on the fish scales, leaving the scales corroded. We can see from the condition of the gar scales in the VMBs that crocs were eating gars back then just as they do now.

These watery ecosystems harbored a variety of amphibians, too. Intriguingly, many of the minute amphibian limb elements and ribs that we recover from our sieves are covered in even tinier tooth marks. These traces were made when a gar fish, a baby crocodile or even a small theropod dinosaur took a bite, scraping its teeth along bone as it did.

Amphibians were not the only creatures that moved between water and land in this ecosystem. Turtles also spent time both in the lake and on terra firma. We've found bony plates from turtle shells with distinc-

The authors and their students explore exposures of the Judith River Formation within the Breaks in search of concentrations of microfossils such as this tooth (*above*) from a carnivorous dinosaur.

Jeff Thole

tive ornamentation patterns characteristic of several soft-shelled turtle species, as well as snapping turtles. Lizards made a home here, too. We have confirmed the presence of several different lizard groups, from close relatives of living iguanas, to long-tailed skinklike forms, to heavily armored insect-eating species.

We also find fossil eggshells in our VMBs. When discovered in isolation, eggs and eggshells can be tricky to link to a particular species. For this reason, there is a special classification system for eggshells called ootaxonomy. We begin by describing the outer and inner surfaces of the shell, noting the color and texture, as well as the distribution of the pores that allowed gas exchange with the developing embryo. Then we look at thin sections of the shell under a microscope to see its crystalline structure. In addition, we can study the chemistry of the eggshells for clues to what types of organisms might have laid these eggs. By assessing fossil eggshells in this way, we have been able to establish that theropod and duck-billed dinosaurs, as well as a variety of crocodiles and turtles nested in the lush lowland environments preserved within the Judith River Formation.

EVERY ONCE IN A WHILE, just when our vision starts to blur after hours of looking at VMB residues through a microscope, we spot something new that isn't a recognizable bone, tooth, or other body part. Sometimes these enigmatic remains turn out to be trace fossils—records of an animal's activity but not part of the animal itself. These fossils, which can be tooth marks (like those seen on the amphibian bones), footprints or feces, among other traces, all signal the presence and behaviors of creatures that we might not detect otherwise.

Small, doughnutlike structures known as gastroliths, or "stomach stones," are one type of trace fossil that occurs in our samples. They show that crayfish lived in the lakes, ponds, rivers and streams of the Breaks back in the Cretaceous. In modern crayfish, gastroliths serve to store calcium carbonate, an essential component of their exoskeletons. When crayfish grow, they must molt their old exoskeleton and build a new, bigger one. Rather than discarding the old armor entirely, they conserve its precious calcium carbonate by sequestering it in gastroliths until they can redeploy it. The gastroliths we find in the Judith River Formation hint that Cretaceous crayfish, like their modern counterparts, were experts at reducing, reusing and recycling.

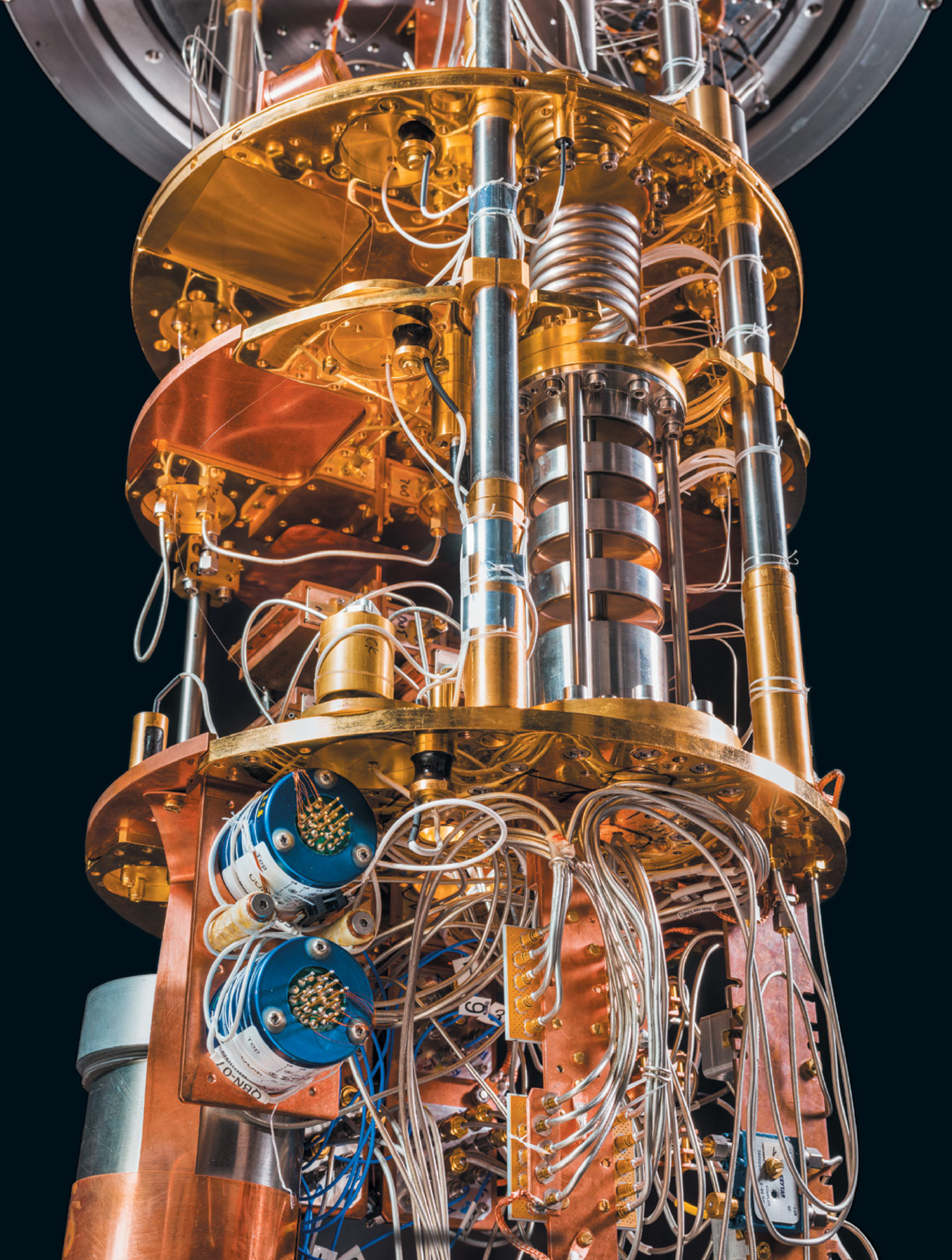
Perhaps the most mysterious trace fossils in our VMBs are igloo-shaped bumps that we frequently find on fragments of clamshells. We puzzled over these peculiar features for years before we finally realized that they are identical to the modern-day structures that form when parasitic flatworms infest clams. The clams build the igloos as an act of self-defense, attempting to contain the invading parasite in a mineralized chamber. We have every reason to believe our Cretaceous clams were doing the same thing to protect themselves.

Parasites tend to have small, squishy bodies—characteristics that do not bode well for fossilization. As a result, scientists usually can't include these ecologically important animals in their reconstructions of fossil food webs. The Judith River VMB clamshell igloos not only confirm the presence of flatworms in this ecosystem but also push back the oldest known occurrence of this type of parasitic interaction between flatworm and clam from just 6,000 or so years ago to 76 million years ago. Modern-day flatworm parasites have complex life cycles involving multiple host species. Clams serve as just one host in the flatworm life cycle, with clam-eating shorebirds often serving as the ultimate host. Maybe in the Cretaceous period flatworms created lines of ecological connection between organisms as different as clams and dinosaurs.

The unassuming fossils of the Judith River Formation VMBs have given us amazing insights into this vibrant lost world of the dinosaurs, more than we ever could have imagined possible. Yet we know there is still so much more to learn. Discoveries like the clamshell igloos underscore what Ferdinand Hayden figured out on his trailblazing journey through the Breaks back in 1855: no fossil is too small or too obscure to reveal amazing, unexpected details about ancient ecosystems. ●

FROM OUR ARCHIVES

Triumph of the Titans. Kristina A. Curry Rogers and Michael D. D'Emic; May 2012.
ScientificAmerican.com/archive



A future quantum computer, far more powerful than this one, will be able to break the cryptographic codes that secure our communications.

MATHEMATICS

Quantum-Proof Secrets

Researchers are racing to create codes that quantum computers can't break

BY KELSEY HOUSTON-EDWARDS

DIGITAL SECURITY EXPERTS around the world have their eyes fixed on the Y2Q—"Years to Quantum"—clock. It ticks down the time until the projected date when a quantum computer will be able to break an essential form of modern cryptography. Called public-key cryptography because of its ingenious method of sharing secret codes in public, it keeps your credit card number safe when you shop online and ensures that your phone's software update is coming from the phone company and not a hacker. Whistleblowers use it to contact journalists, and businesses use it to send confidential files.

Kelsey Houston-Edwards is a mathematician and journalist. She formerly wrote and hosted the online show *PBS Infinite Series.*

But a quantum computer would render the standard types of public-key cryptography useless. "This is really very serious," says Bruno Huttner, co-chair of the Quantum-Safe Security Working Group at the Cloud Security Alliance. "If there was a quantum computer tomorrow, we wouldn't be able to talk together with any kind of security."

Huttner is one of the creators of the Y2Q clock, named in analogy to the Y2K crisis of the late 1990s. Twentieth-century software programs had denoted years by only two digits, which meant that to computers, 2000 was "00"—the same as 1900. Programs involving such a date were expected to malfunction when the new millennium arrived, causing potentially massive disruptions. But in the end, no banks collapsed, no power grids shut down and no airplanes fell from the sky when the year changed. The transition was seamless—mostly because businesses and governments had raced to fix the Y2K bug.

No one knows exactly when a quantum computer large enough to break cryptographic standards will be developed. The current end date on the Y2Q clock, April 14, 2030, is just a guess. But most researchers believe the shift will happen within the next few decades. "The threat is coming," Huttner says, and the Y2Q clock is a reminder. "Putting a date on it helps people to focus."

For governments and other institutions that need to keep secrets for the long term, the real deadline is much sooner. If encrypted data sent today get stored, then a future quantum computer could retroactively decrypt the messages. "If you need to keep a secret for 20 years, and you think that quantum computers that break your cryptography might emerge within 20 years, you have a problem today," says computer scientist Chris Peikert of the University of Michigan.

Anticipating this threat, the National Institute of Standards and Technology (NIST) initiated a public contest in 2016. It solicited ideas for "post-quantum" or "quantum-resistant" cryptography—codes that can run on today's computers but are so robust that not even quantum computers could break them. Underscoring the urgency, in December 2022 the U.S. Congress passed the Quantum Computer Cybersecurity Preparedness Act, which requires government agencies to create a plan for transitioning to such algorithms.

Christopher Payne/Esto (*preceding pages*)

Four rounds of submissions and appraisals later, NIST selected a winner, called CRYSTALS-Kyber, in the category of public-key encryption and three winners in the category of digital signatures, used for securely identifying the sender of a message. NIST is now working with researchers to standardize the winning algorithms so programmers can start laying the foundations of quantum-proof secret-keeping.

Somewhat worryingly, however, three of the four selected algorithms, including CRYSTALS-Kyber, are based on the mathematics of lattices. Experts are confident that these are very hard problems to solve—but no one can guarantee that a future breakthrough won't crack them open.

ONE OF THE EARLIEST known forms of cryptography is a cipher that was used to substitute letters in a piece of writing. In his messages, Julius Caesar replaced each letter with one three positions away in the Roman alphabet. In English, that would mean "a" becomes "d," "b" becomes "e," and so on. To decrypt a message from Caesar, you would simply reverse the process, shifting the letters by three alphabetical positions.

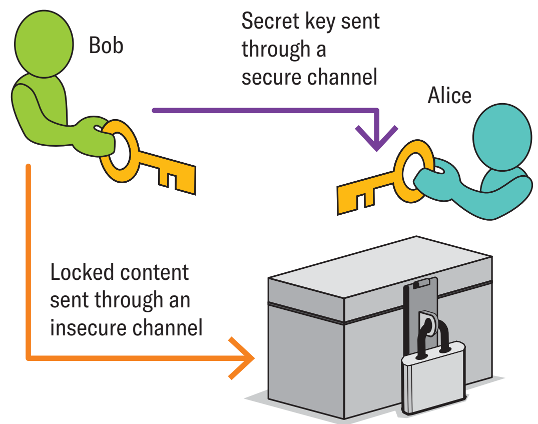
There are endless variations of Caesar's substitution scheme—children passing notes in class could create their own, replacing "a" with a heart, "b" with a star, and so on—but they are easy to break. A teacher who confiscates a child's note might notice that it contains many isolated triangles, representing a one-letter word, and deduce that the triangle stands for "I" or "a." Code breakers can usually solve more complicated substitution schemes by comparing the frequency of different symbols with those of letters in common English texts.

The gold standard in modern cryptography, known as the Advanced Encryption Standard, or AES, dramatically expands on Caesar's approach. It scrambles the message by repeatedly substituting the entries and shuffling them like a deck of playing cards. After enough shuffles and substitutions, it's very difficult to reconstruct the original version.

To decrypt the message, you would have to unscramble it by undoing each shuffle and substitution. With a physical deck of cards, this is nearly impossible—the shuffling order is determined by imperceptibly slight movements. But a computer shuffles the message according to a precise set of instructions—for example, "move the second entry into the fifth spot"—that are easy to undo. The computer simply follows the instructions in reverse: "move the fifth entry into the second spot."

Like Caesar's cipher, AES has symmetrical procedures for encrypting and decrypting. It applies the same process forward and backward, just like twisting a key in opposite directions to lock and unlock a door. Until the 1970s, so-called symmetric cryptography (also known as symmetric-key cryptography) was the only type of cryptography. But it has a major limitation: the sender and receiver need to agree on the procedure for encryption and decryption before exchanging any messages, either in person or through a trusted, separate mode of communication.

Symmetric Cryptography



It's hard to imagine an alternative to symmetric cryptography without this constraint. In 1974, when University of California, Berkeley, undergraduate student Ralph Merkle proposed a class project investigating methods for "two people to communicate securely without having made any prior arrangements," he anticipated how outrageous the idea might seem and added, "No, I am not joking." Merkle envisioned a system in which two people exchange messages entirely in the open, always assuming someone is listening. Through this public correspondence, they manage to establish a scheme for coding and decoding and use it to send secret messages. If someone else were reading the messages, they wouldn't be able to figure out the scheme. Merkle's proposal was rejected by an expert for having "unrealistic working assumptions."

Remarkably, however, several mathematics papers realized Merkle's vision just a few years later. Two of the proposed algorithms, called Diffie-Hellman and RSA (short for Rivest-Shamir-Adleman, the surnames of its creators), are ubiquitous in modern communications. As it turns out, even before Merkle's class project, researchers at a British intelligence organization had discovered such coding—public-key cryptography—and kept it a secret.

WHEN YOU CHECK your bank account online, your computer and the bank's server are exchanging messages: you send your password, and the bank sends your balance. While that information moves through the Internet, someone else could read it. The messages need to be encrypted.

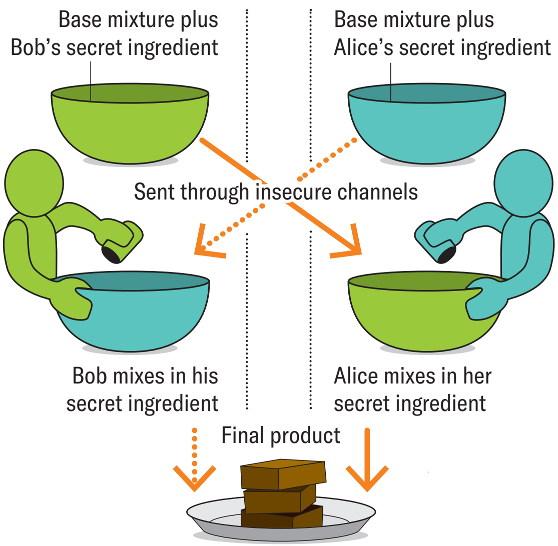
Most messages are encrypted with symmetric cryptography, such as AES, which quickly and efficiently scrambles them. But first your computer and the communicating server need to agree on the specific scrambling procedure. They can't simply

Graphics by Jen Christiansen

write it down, because all their communications could be captured by an eavesdropper. They need to use public-key cryptography.

To understand how this process works, let's imagine that two friends, Alice and Bob, own a bakery with a top-secret brownie recipe. It's so secret that even Alice and Bob don't know the full recipe. They each add a special ingredient known only to the person who adds it. To create the brownies, Alice and Bob trade off days starting the recipe. Sometimes Alice mixes up basic ingredients with her secret one and sends the batter to Bob, who adds his secret ingredient and bakes it. Other times Bob first combines the basic ingredients with his secret one before shipping it to Alice, who mixes in her secret ingredient and bakes the brownies.

Public-Key Cryptography



Alice and Bob always end up with the same brownies—but they never share the full, exact ingredients with anyone, including each other. Even their conniving delivery driver, Eve, can't figure out the recipe. (In cryptography, the two people exchanging secrets are traditionally named Alice and Bob, and a potential spy is often named Eve.) Eve can't deduce the secret ingredients, because whenever she transports them, they're mixed in with all the basic ingredients—it is impossible to separate them.

Of course, computers don't bake brownies. They work with numbers and math. In real public-key cryptography, the goal is to end up with a shared secret number—something like a temporary password that grants access to a private conversation. The two computers can then continue to have an encrypted conversation using symmetric cryptography such as AES.

Different types of public-key cryptography create and share the temporary password in different ways. Alice and Bob hid their brownie recipe from Eve by mixing the ingredients before transporting them. Someone implementing public-key cryptography would instead use mathematical functions to blend secret numbers.

Functions are like machines that take in numbers, churn them up and spit out a new number. The functions used in public-key cryptography are very particular. They need to mix up numbers easily while making them very hard to unmix. Even if Eve sees the output of the function, she shouldn't be able to guess which secret numbers went in as input.

RSA cryptography, for example, is based on the multiplication function and its opposite, factoring. Mixing numbers by multiplying them is relatively easy for a computer even if the numbers are very large. But undoing multiplication, or factoring, is very hard if the numbers are large. (Factoring means answering the question, What numbers do I have to multiply together to get this number? For example, factoring 21 yields three and seven.) Decrypting a password created with RSA would require factoring a large number. The best methods involve filtering through many numbers to find a particular combination of them—which takes a computer a very long time.

"Rather than trying to make cryptographic schemes more and more complicated," says computer scientist Boaz Barak of Harvard University, "we have actually moved to cryptography that is based on very, very simple things like integer factoring, which has been studied for thousands of years."

IN 1994 APPLIED MATHEMATICIAN Peter Shor, then a research scientist at Bell Labs, discovered a way in which a quantum computer could break any code encrypted with RSA or Diffie-Hellman. As Shor told me, he had attended a talk about using quantum computers to solve math problems with a periodic, or repeating, structure. It reminded him of the "discrete logarithm" problem. A logarithmic function is the inverse of an exponential function—for example, finding x in the equation $2^x = 16$.

Usually it's easy to find the logarithm, but the discrete logarithm problem is about computing the logarithm using alternative forms of arithmetic in which one counts in a circle, like on a clock. Just as RSA is based on factoring, Diffie-Hellman is based on the discrete logarithm problem. Computer scientists generally believe that there is no quick way to find the discrete logarithm with a classical computer. But Shor found a way to do it on a quantum computer. He then applied similar logic to show how to use a quantum computer to quickly factor large numbers. Together these solutions are known as Shor's algorithm.

Shor wasn't imagining programming a real quantum computer—he was simply doing math on chalkboards and paper. "At the time quantum computers seemed like they were way, way far in the future," Shor says. "So mainly I was thinking that it was a very nice mathematical theorem." But his algorithm has major implications for public-key cryptography. A quantum computer could use it to break almost all cryptographic systems currently in use.

Classical computers run on long strings of 0s and 1s known as bits, but quantum computers use qubits, a portmanteau of "quantum" and "bit." Qubits can be in a superposition—strange combinations of 0s and 1s. By hovering between the two states, qubits enable quantum computers to perform certain tasks much faster than classical computers. But quantum computers are finicky. The qubits need to maintain a superposition while the algorithm is running, but they tend to "collapse" into a string of 0s and 1s.

Quantum computers look impressive—they dangle from the ceiling like massive gold chandeliers—but they're still not very powerful. Scientists have been able to run computations with only a modest number of qubits, and the largest number they have factored on a quantum computer using Shor's algorithm is 21. In 2012 researchers at the University of Bristol in England used a quantum computer to deduce that 21 is three times seven.

Many experts believe that a quantum computer large enough to break RSA and Diffie-Hellman will be built within the next few decades, but they're quick to admit that the time line is uncertain. For cryptographers, who need to race ahead of quantum computers, the uncertainty is concerning. "Each industry has a certain aspect of their work that makes it very significant for them," says Ray Harishankar of IBM. Healthcare companies need to secure the data they use in medical research, and power companies must protect the electric grid from hackers. "Worst-case scenario: if something bad happens, they're totally exposed," Harishankar says.

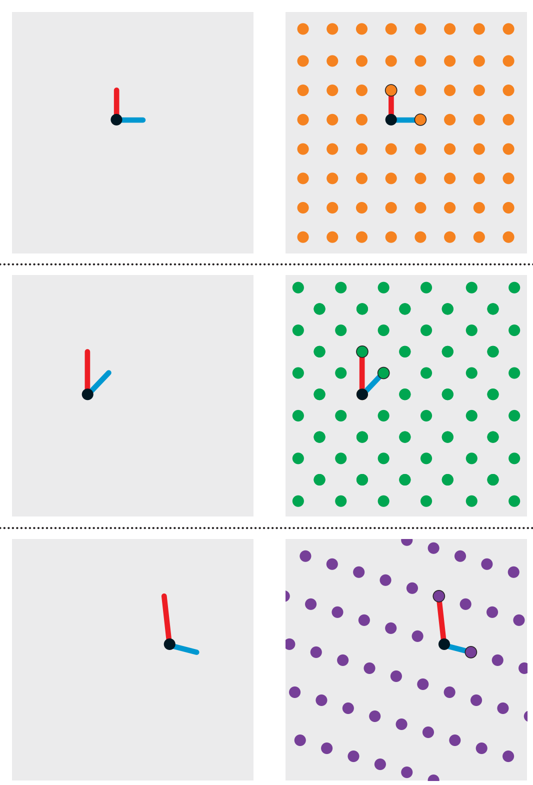
Every type of public-key cryptography is grounded in a hard math problem. To secure secrets against a quantum future, researchers need to use problems so hard that even a quantum computer cannot solve them in a reasonable amount of time. The NIST challenge sought nominations for public-key cryptographic algorithms that could be widely implemented on standard computers as alternatives to RSA and Diffie-Hellman. The many different connected systems and devices that people use must all "talk this new type of cryptography with one another," says Lily Chen, a mathematician at NIST.

Before the deadline in 2017, researchers submitted 82 different proposals for post-quantum cryptography. (Confusingly, "quantum cryptography" refers to something else—using quantum phenomena as part of the security scheme.) Over the next year researchers tested the algorithms, and then NIST experts selected 26 algorithms that would continue to the next round.

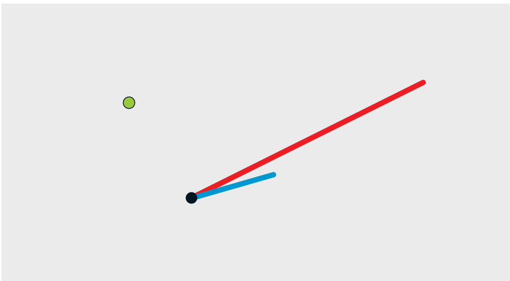
Public input is an essential part of the NIST contest. Cryptographic systems aren't guaranteed to be secure, so researchers try to poke holes in them. One of the candidate algorithms used "isogeny-based" cryptography, which had been studied for a decade and seemed promising. But two researchers noticed that a 25-year-old mathematics theorem could be used to crack that algorithm. It took them just one hour using a standard laptop.

NIST experts eventually settled on several finalist algorithms, most of which were based on lattice mathematics. "Lattices were a natural choice," says Vadim Lyubashevsky of IBM, one of the authors of CRYSTALS-Kyber. "People have been working on this in various guises for more than two decades already."

A LATTICE IS A REPEATING ARRAY of dots. One of the simplest looks like a pegboard—dots arranged in a square grid. Mathematicians think of this lattice as being constructed from two foundational lines: a vertical one and horizontal one of equal length. Imagine drawing a point in the center of a piece of paper, drawing a series of vertical or horizontal lines, all of equal length, extending out from that center and marking the points where the chains of lines end. If you repeat these steps for all possible chains, the dots will form a square grid. Different sets of initial lines create different lattices. The two lines may have unequal lengths, or instead of being perfectly horizontal or vertical, they could be tilted at an angle. Drawing chains of such lines would still yield a repetitive pattern of dots but with the rows and columns offset or of different heights.



Lattices are the backdrop for some deceptively tricky math problems. Suppose I draw two lines on a piece of paper and tell you that they are the building blocks of a lattice. Then I draw a single dot somewhere on the page. Could you find the lattice point that is closest to that dot?



You could probably use the foundational lines to start drawing the lattice points and eventually find the closest one. But that would be possible only because the lattice on the paper is two-dimensional. Our visual imaginations are generally limited to three dimensions, but mathematicians can describe lattices with hundreds of dimensions. In those it is very difficult to find the nearest lattice point.

Researchers use such massive lattices to build cryptographic systems. For example, start with a 1,000-dimensional lattice. Out of this sea of dots, select a single point. The precise location of this point represents the secret message. Then wiggle a little bit away from this point, floating off the lattice into the ambient space. You can share the new location publicly without giving away the location of the secret point—finding nearby lattice points is a very hard math problem. Just like mixing the ingredients protects the brownie recipe, wiggling away from the secret point obscures its precise location.

Computer scientists have been studying such problems for decades and are reasonably confident that they're very hard to solve. But when designing a new algorithm, cryptographers need to balance security with many other concerns, such as the amount of information two computers need to exchange and the difficulty of the computation required to encrypt and decrypt messages. In this respect, lattice-based cryptography excels. "Lattices fit into this sweet spot where everything is reasonable—nothing is too bad, nothing is too good," Peikert says. "It's sort of like Goldilocks."

THE PROBLEM IS, no one can guarantee that lattice-based cryptography will always be secure. To guard against a mathematical breakthrough solving the underlying problem—and breaking the code—cryptographers need access to a variety of algorithm types. But three of the four finalists in the NIST process were lattice-based algorithms. The only one selected for standardization in the general public-key encryption category was CRYSTALS-Kyber.

The NIST contest also has a category for digital-signature algorithms, which provide guarantees about who sent the message and that it wasn't modified. Encryption algorithms answer the question, "Do I know that no one else will be reading this?" explains cryptographer Britta Hale of the Naval Postgraduate School in Monterey, Calif., whereas digital signatures answer the question, "Can I trust these data have not been modified?" The digital-signature algorithms currently in use are also vulnerable to Shor's algorithm. NIST chose to standardize three digital-signature algorithms, two of which are lattice-based.

Such heavy reliance on a single type of math problem is risky. No one can be certain that mathematicians won't eventually crack it. Nor does it give users any flexibility—it could turn out that another type of cryptography fits their specific needs better. For these reasons, NIST has extended the standardization process in both categories to study algorithms that are not lattice-based. "Our goal in this is not to depend on any one mathematical family for the algorithms we select," explains Dustin Moody, a mathematician at NIST.

Even the algorithms already selected for standardization needed to be tweaked along the way. After the first round of submissions, researchers noticed that CRYSTALS-Kyber had a small issue, which the authors addressed. And during a later round of the contest, they found a way to slightly improve the algorithm. "We changed the parameters to get a few more bits of security," says Peter Schwabe of the Max Planck Institute for Security and Privacy in Bochum, Germany, who is one of the creators of CRYSTALS-Kyber.

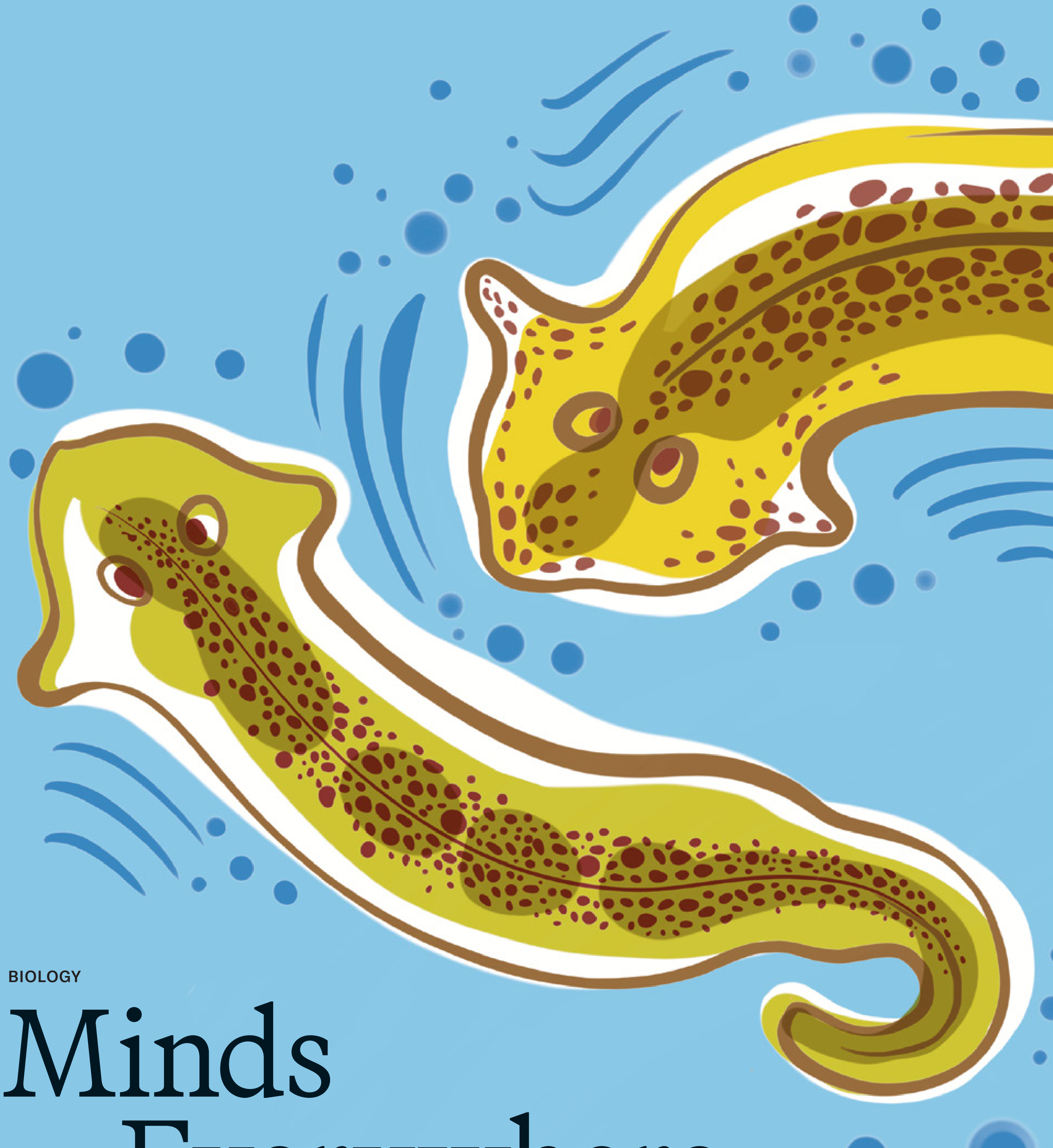
NIST is now in the process of setting the standards, which describe in step-by-step detail how computer programmers should implement the algorithms. "Everything on the Internet must have superspecific, superboring standards with every little detail. Otherwise computers just can't talk to one another," Lyubashevsky says. After the standards are set, every computer system needs to switch to post-quantum cryptography. There is no one moment when everyone flips a switch. Individual software companies need to upgrade their protocols, governments need to change their requirements, and physical hardware devices need to be swapped out.

It will probably take many years, if not decades, to fully transition to post-quantum cryptography. Until that happens, any messages sent with the old forms of cryptography will be potentially readable with a future quantum computer. Depending on how long you're hoping to keep a secret, the time for concern might already have passed. As Hale says, "On the cryptographic side, everyone is looking at their watches, saying, 'You're past due.'"

FROM OUR ARCHIVES
The Math of Making Connections. Kelsey Houston-Edwards; April 2021. ScientificAmerican.com/archive

To protect their fragile quantum behavior, quantum computers must be isolated from their environments and supercooled. The hanging apparatus enables the computer, which is encased in a compartment at the bottom, to be cooled.

Christopher Payne/Esto



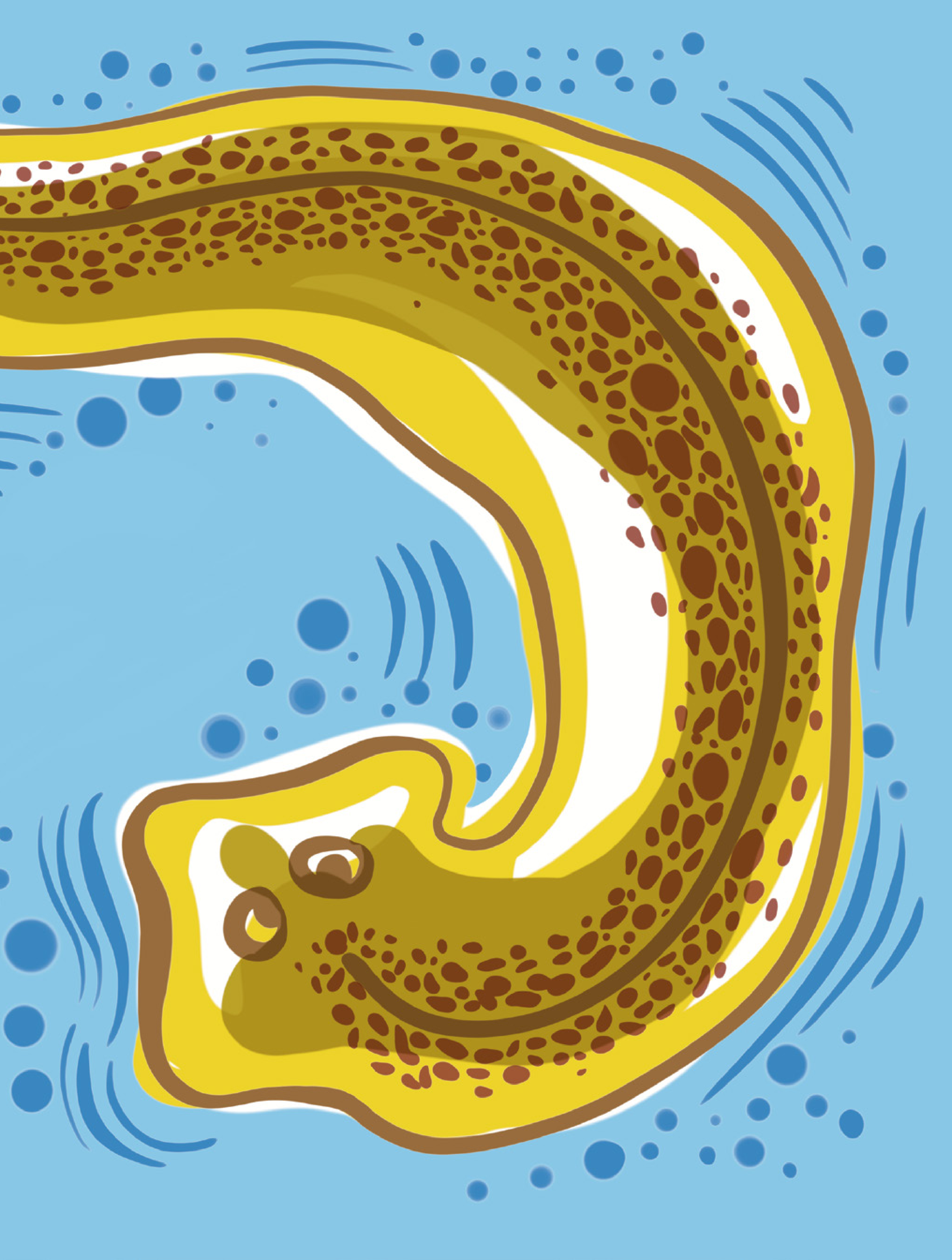
BIOLOGY

Minds Everywhere

Tiny clumps of cells can learn, form memories and make big decisions—key parts of thinking. Yet they don't have brains

BY ROWAN JACOBSEN

ILLUSTRATIONS BY NATALYA BALNOVA



T**HE PLANARIAN** is nobody's idea of a genius. A flatworm shaped like a comma, it can be found wriggling through the muck of lakes and ponds worldwide. Its pin-size head has a microscopic structure that passes for a brain. Its two eyespots are set close together in a way that makes it look cartoonishly confused. It aspires to nothing more than life as a bottom-feeder.

But the worm has mastered one task that has eluded humanity's greatest minds: perfect regeneration. Tear it in half, and its head will grow a new tail while its tail grows a new head. After a week two healthy worms swim away.

Growing a new head is a neat trick. But it's the tail end of the worm that intrigues Tufts University biologist Michael Levin. He studies the way bodies develop from single cells, among other things, and his research led him to suspect that the intelligence of living things lies outside their brains to a surprising degree. Substantial smarts may be in the cells of a worm's rear end, for instance. "All intelligence is really collective intelligence, because every cognitive system is made of some kind of parts," Levin says. An animal that can survive the complete loss of its head was Levin's perfect test subject.

In their natural state planaria prefer the smooth and sheltered to the rough and open. Put them in a dish with a corrugated bottom, and they will huddle against the rim. But in his laboratory, about a decade ago, Levin trained some planaria to expect yummy bits of liver puree that he dripped into the middle of a ridged dish. They soon lost all fear of the rough patch, eagerly crossing the divide to get the treats. He trained other worms in the same way but in smooth dishes. Then he decapitated them all.

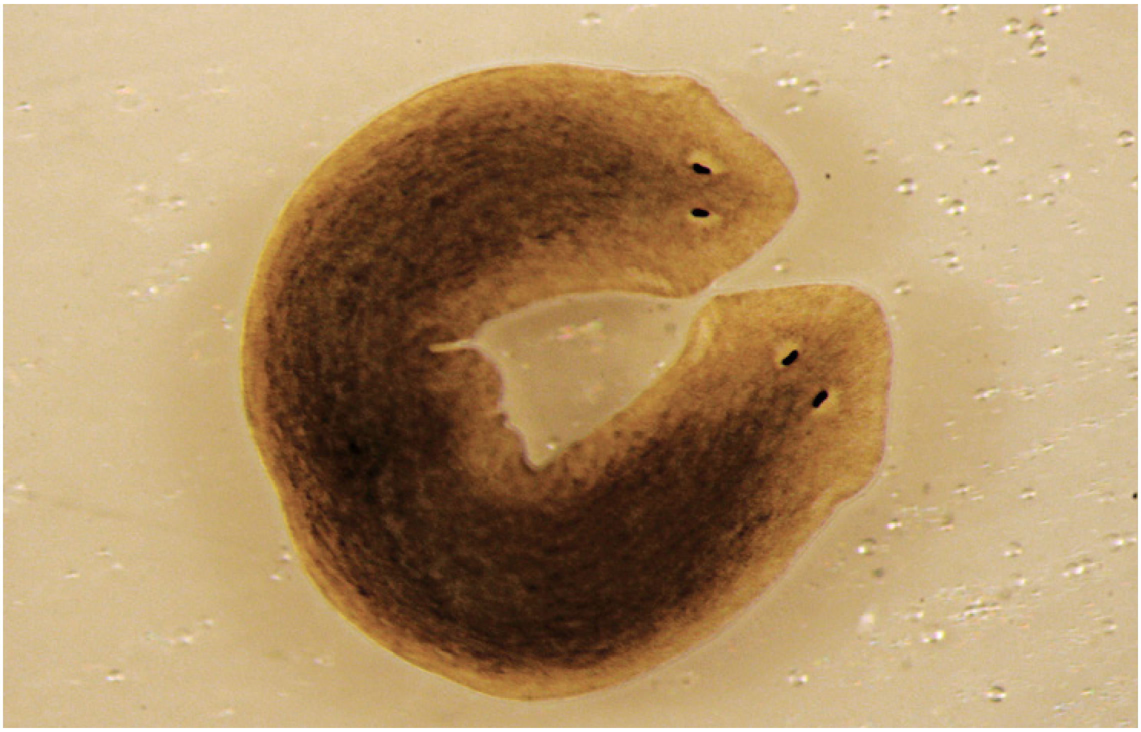
Levin discarded the head ends and waited two weeks while the tail ends regrew new heads. Next he placed the regenerated worms in corrugated dishes and dripped liver into the center. Worms that had lived in a smooth dish in their previous incarnation were reluctant to move. But worms regenerated from tails that had lived in rough dishes learned to go for the food more quickly. Somehow, despite the total loss of their brains, those planaria had retained the memory of the liver reward. But how? Where?

It turns out that regular cells—not just highly specialized brain cells such as neurons—have the ability to store information and act on it. Now Levin has shown that the cells do so by using subtle changes in electric fields as a type of memory. These revelations have put the biologist at the vanguard of a new field called basal cognition. Researchers in this burgeoning area have spotted hallmarks of intelligence—learning, memory, problem-solving—outside brains as well as within them.

Until recently, most scientists held that true cognition arrived with the first brains half a billion years ago. Without intricate clusters of neurons, behavior was merely a kind of reflex. But Levin and several other researchers believe otherwise. He doesn't deny that brains are awesome, paragons of computational speed and power. But he sees the differences between cell clumps and brains as ones of degree, not kind. In fact, Levin suspects that cognition probably evolved as cells started to collaborate to carry out the incredibly difficult task of building complex organisms and then got souped-up into brains to allow animals to move and think faster.

That position is being embraced by researchers in a variety of disciplines, including roboticists such as Josh Bongard, a frequent Levin collaborator who runs the Morphology, Evolution, and Cognition Laboratory at the University of Vermont. "Brains were one of the most recent inventions of Mother Nature, the thing that came last," says Bongard, who hopes to build deeply intelligent machines from the bottom up. "It's clear that the body matters, and then somehow you add neural cognition on

Rowan Jacobsen is a journalist and author of several books, including *Truffle Hound* (Bloomsbury, 2021). He wrote about cracking the code that makes artificial proteins in *Scientific American*'s July 2021 issue.



Head cells in the flatworm *Dugesia japonica* have different bioelectric voltages than tail cells do. Switch the voltages around and cut off the tail, and the head will regenerate a second head.

Michael Levin

top. It's the cherry on the sundae. It's not the sundae."

In recent years interest in basal cognition has exploded as researchers have recognized example after example of surprisingly sophisticated intelligence at work across life's kingdoms, no brain required. For artificial-intelligence scientists such as Bongard, basal cognition offers an escape from the trap of assuming that future intelligences must mimic the brain-centric human model. For medical specialists, there are tantalizing hints of ways to awaken cells' innate powers of healing and regeneration.

And for the philosophically minded, basal cognition casts the world in a sparkling new light. Maybe thinking builds from a simple start. Maybe it is happening all around us, every day, in forms we haven't recognized because we didn't know what to look for. Maybe minds are everywhere.

ALTHOUGH IT NOW SEEMS like a Dark Ages idea, only a few decades ago many scientists believed that nonhuman animals couldn't experience pain or other emotions. Real thought? Out of the question. The mind was the purview of humans. "It was the last beachhead," says Pamela Lyon of the University of Adelaide, a scholar of basal cognition, who coined the term for the field in 2018. Lyon sees scientists' insistence that human intelligence is qualitatively different as just another doomed form of exceptionalism. "We've been ripped from every central position we've inhabited," she points out. Earth is not the center of the universe. People are just another animal species. But real cognition—that was supposed to set us apart.

Now that notion, too, is in retreat as researchers document the rich inner lives of creatures increasingly distant from us. Apes, dogs, dolphins, crows and even insects are proving more savvy than suspected. In his 2022 book *The Mind of a Bee,* behavioral ecologist Lars Chittka chronicles his decades of work with honeybees, showing that bees can use sign language, recognize individual human faces, and remember and convey the locations of far-flung flowers. They have good moods and bad, and they can be traumatized by near-death experiences such as being grabbed by an animatronic spider hidden in a flower. (Who wouldn't be?)

But bees, of course, are animals with actual brains, so a soupçon of smarts doesn't really shake the paradigm. The bigger challenge comes from evidence of surprisingly sophisticated behavior in our brainless relatives. "The neuron is not a miracle cell," says Stefano Mancuso, a University of Florence botanist who has written several books on plant intelligence. "It's a normal cell that is able to produce an electric signal. In plants almost every cell is able to do that."

On one plant, the touch-me-not, feathery leaves normally fold and wilt when touched (a defense mechanism against being eaten), but when a team of scientists at the University of Western Australia and the University of Firenze in Italy conditioned the plant by jostling it throughout the day without harming it, it quickly learned to ignore the stimulus. Most remarkably, when the scientists left the plant alone for a month and then retested it, it remembered the experience. Other plants have other abilities. A Venus flytrap can count, snapping shut only if two of the sensory hairs on its trap are tripped in quick succession and pouring digestive juices into the closed trap only if its sensory hairs are tripped three more times.

These responses in plants are mediated by electric signals, just as they are in animals. Wire a flytrap to a touch-me-not, and you can make the entire touch-me-

Clumps of Cognition

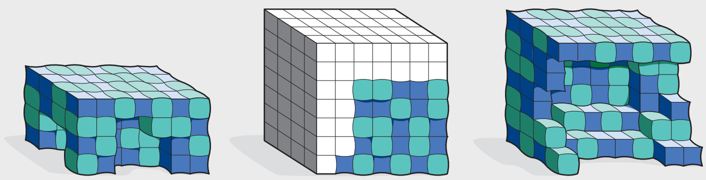
Brains, or brain cells, are not the only cell groupings in the body that show the ability to "think." Living robots called xenobots have been constructed from skin and heart cells taken from the African clawed frog. (The frog genus is *Xenopus,* hence the name.) Even when arranged in forms not found in nature, the cells can interpret their environment and share enough information to accomplish simple goals, such as moving in a particular direction.

BUILDING A BOT

The design started in a supercomputer at the University of Vermont, with simulated blocks that had a few basic rules about motion. Some were passive, like frog skin cells (*white*). Others, like heart muscle cells, expanded (*green*) or contracted (*blue*).

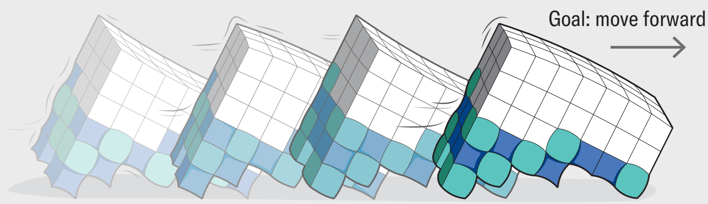
EVOLUTION IN A MACHINE

The supercomputer program began by arranging the blocks into multitudes of random shapes. In each of these shapes, the constituent blocks followed their built-in rules of expanding, contracting or doing essentially nothing.



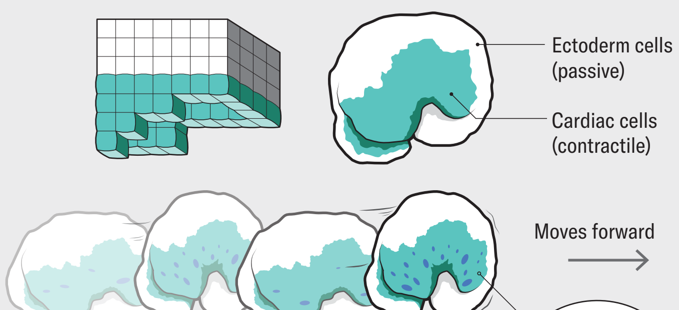
UNNATURAL SELECTION

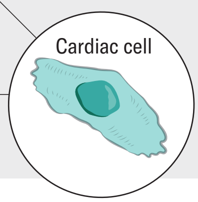
The program began to filter the shapes, highlighting those that best achieved a goal in their simulated environment: moving forward. The best-performing shapes became the basis for next-generation designs that did even better.



GOING LIVE

Using microsurgery, scientists at Tufts University took frog skin (ectoderm) stem cells and heart stem cells and arranged them to mimic the most effective computer design. Those cells began to coordinate contraction and expansion to move in a dish.





COHERENT MOTION

Heart or skin cells do not have inherent instructions to move in any one direction. But when placed in a xenobot configuration, they communicate to achieve that goal.

not collapse by touching a sensory hair on the flytrap. And these and other plants can be knocked out by anesthetic gas. Their electric activity flatlines, and they stop responding as if unconscious.

Plants can sense their surroundings surprisingly well. They know whether they are being shaded by part of themselves or by something else. They can detect the sound of running water (and will grow toward it) and of bees' wings (and will produce nectar in preparation). They know when they are being eaten by bugs and will produce nasty defense chemicals in response. They even know when their neighbors are under attack: when scientists played a recording of munching caterpillars to a cress plant, that was enough for the plant to send a surge of mustard oil into its leaves.

Plants' most remarkable behavior tends to get underappreciated because we see it every day: they seem to know exactly what form they have and plan their future growth based on the sights, sounds and smells around them, making complicated decisions about where future resources and dangers might be located in ways that can't be boiled down to simple formulas. As Paco Calvo, director of the Minimal Intelligence Laboratory at the University of Murcia in Spain and author of *Planta Sapiens,* puts it, "Plants have to plan ahead to achieve goals, and to do so, they need to integrate vast pools of data. They need to engage with their surroundings adaptively and proactively, and they need to think about the future. They just couldn't afford to do otherwise."

None of this implies that plants are geniuses, but within their limited tool set, they show a solid ability to perceive their world and use that information to get what they need—key components of intelligence. But again, plants are a relatively easy case—no brains but lots of complexity and trillions of cells to play with. That's not the situation for single-celled organisms, which have traditionally been relegated to the "mindless" category by virtually everyone. If amoebas can think, then humans need to rethink all kinds of assumptions.

Yet the evidence for cogitating pond scum grows daily. Consider the slime mold, a cellular puddle that looks a bit like melted Velveeta and oozes through the world's forests digesting dead plant matter. Although it can be the size of a throw rug, a slime mold is one single cell with many nuclei. It has no nervous system, yet it is an excellent problem solver. When researchers from Japan and Hungary placed a slime mold at one end of a maze and a pile of oat flakes at the other, the slime mold did what slime molds do, exploring every possible option for tasty resources. But once it found the oat flakes, it retreated from all the dead ends and concentrated its body in the path that led to the oats, choosing the shortest route through the maze (of four possible solutions) every time. Inspired by that experiment, the same researchers then piled oat flakes around a slime mold in positions and quantities meant to represent the population structure of Tokyo, and the slime mold contorted itself into a very passable map of the Tokyo subway system.

Source: "A Scalable Pipeline for Designing Reconfigurable Organisms," by Sam Kriegman et al., in *PNAS,* Vol. 117; January 2020 (*reference*)

Graphic by Brown Bird Design

Such problem-solving could be dismissed as simple algorithms, but other experiments make it clear that slime molds can learn. When Audrey Dussutour of France's National Center for Scientific Research placed dishes of oatmeal on the far end of a bridge lined with caffeine (which slime molds find disgusting), slime molds were stymied for days, searching for a way across the bridge like an arachnophobe trying to scooch past a tarantula. Eventually they got so hungry that they went for it, crossing over the caffeine and feasting on the delicious oatmeal, and soon they lost all aversion to the formerly distasteful stuff. They had overcome their inhibitions and learned from the experience, and they retained the memory even after being put into a state of suspended animation for a year.

Which brings us back to the decapitated planaria. How can something without a brain remember anything? Where is the memory stored? *Where is its mind?*

THE ORTHODOX VIEW of memory is that it is stored as a stable network of synaptic connections among neurons in a brain. "That view is clearly cracking," Levin says. Some of the demolition work has come from the lab of neuroscientist David Glanzman of the University of California, Los Angeles. Glanzman was able to transfer a memory of an electric shock from one sea slug to another by extracting RNA from the brains of shocked slugs and injecting it into the brains of new slugs. The recipients then "remembered" to recoil from the touch that preceded the shock. If RNA can be a medium of memory storage, any cell might have the ability, not just neurons.

Indeed, there's no shortage of possible mechanisms by which collections of cells might be able to incorporate experience. All cells have lots of adjustable pieces in their cytoskeletons and gene regulatory networks that can be set in different conformations and can inform behavior later on. In the case of the decapitated planaria, scientists still don't know for sure, but perhaps the remaining bodies were storing information in their cellular interiors that could be communicated to the rest of the body as it was rebuilt. Perhaps their nerves' basic response to rough floors had already been altered.

Levin, though, thinks something even more intriguing is going on: perhaps the impression was stored not just within the cells but in their states of interaction through bioelectricity, the subtle current that courses through all living things. Levin has spent much of his career studying how cell collectives communicate to solve sophisticated challenges during morphogenesis, or body building. How do they work together to make limbs and organs in exactly the right places? Part of that answer seems to lie in bioelectricity.

The fact that bodies have electricity flickering through them has been known for centuries, but until quite recently most biologists thought it was mostly used to deliver signals. Shoot some current through a frog's nervous system, and the frog's leg kicks. Neurons used bioelectricity to transmit information, but most scientists believed that was a specialty of brains, not bodies.

Since the 1930s, however, a small number of researchers have observed that other types of cells seem to be using bioelectricity to store and share information. Levin immersed himself in this unconventional body of work and made the next cognitive leap, drawing on his background in computer science. He'd supported himself during school by writing code, and he knew that computers used electricity to toggle their transistors between 0 and 1 and that all computer programs were built up from that binary foundation. So as an undergraduate, when he learned that all cells in the body have channels in their membranes that act like voltage gates, allowing different levels of current to pass through them, he immediately saw that such gates could function like transistors and that cells could use this electricity-driven information processing to coordinate their activities.

To find out whether voltage changes really altered the ways that cells passed information to one another, Levin turned to his planaria farm. In the 2000s he designed a way to measure the voltage at any point on a planarian and found different voltages on the head and tail ends. When he used drugs to change the voltage of the tail to that normally found in the head, the worm was unfazed. But then he cut the planarian in two, and the head end regrew a second head instead of a tail. Remarkably, when Levin cut the new worm in half, both heads grew new heads. Although the worms were genetically identical to normal planaria, the one-time change in voltage resulted in a permanent two-headed state.

For more confirmation that bioelectricity could control body shape and growth, Levin turned to African clawed frogs, common lab animals that quickly metamorphose from egg to tadpole to adult. He found that he could trigger the creation of a working eye anywhere on a tadpole by inducing a particular voltage in that spot. By simply applying the right bioelectric signature to a wound for 24 hours, he could induce regeneration of a functional leg. The cells took it from there.

"It's a subroutine call," Levin says. In computer programming, a subroutine call is a piece of code—a kind of shorthand—that tells a machine to initiate a whole suite of lower-level mechanical actions. The beauty of this higher level of programming is that it allows us to control billions of circuits without having to open up the machine and mechanically alter each one by hand. And that was the case with building tadpole eyes. No one had to micromanage the construction of lenses, retinas, and all the other parts of an eye. It could all be controlled at the level of bioelectricity. "It's literally the cognitive glue," Levin says. "It's what allows groups of cells to work together."

Levin believes this discovery could have profound implications not only for our understanding of the evolution of cognition but also for human medicine. Learning to "speak cell"—to coordinate cells' behavior through bioelectricity—might help us treat cancer, a disease that occurs when part of the body stops cooperating with the rest of the body. Normal cells are programmed to function as part of the collective, sticking to the tasks assigned—liver cell, skin cell, and so on. But cancer cells stop doing their job and begin treating the surrounding body like an unfamiliar environment, striking out on their own to seek nourishment, replicate and defend themselves from attack. In other words, they act like independent organisms.

Why do they lose their group identity? In part, Levin says, because the mechanisms that maintain the cellular mind meld can fail. "Stress, chemicals, genetic mutations can all cause a breakdown of this communication," he says. His team has been able to induce tumors in frogs just by forcing a "bad" bioelectric pattern onto healthy tissue. It's as if the cancer cells stop receiving their orders and go rogue.

Even more tantalizingly, Levin has dissipated tumors by reintroducing the proper bioelectric pattern—in effect reestablishing communication between the breakaway cancer and the body, as if he's bringing a sleeper cell back into the fold. At some point in the future, he speculates, bioelectric therapy might be applied to human cancers, stopping tumors from growing. It also could play a role in regenerating failing organs—kidneys, say, or hearts—if scientists can crack the bioelectric code that tells cells to start growing in the right patterns. With tadpoles, in fact, Levin showed that animals suffering from massive brain damage at birth were able to build normal brains after the right shot of bioelectricity.

LEVIN'S RESEARCH has always had tangible applications, such as cancer therapy, limb regeneration and wound healing. But over the past few years he's allowed a philosophical current to enter his papers and talks. "It's been sort of a slow rollout," he confesses. "I've had these ideas for decades, but it wasn't the right time to talk about it."

That began to change with a celebrated 2019 paper entitled "The Computational Boundary of a Self," in which he harnessed the results of his experiments to argue that we are all collective intelligences built out of smaller, highly competent problem-solving agents. As Vermont's Bongard told the *New York Times,* "What we are is intelligent machines made of intelligent machines made of intelligent machines all the way down."

For Levin, that realization came in part from watching the bodies of his clawed frogs as they developed. In frogs' transformation from tadpole to adult, their faces undergo massive remodeling. The head changes shape, and the eyes, mouth and nostrils all migrate to new positions. The common assumption has been that these rearrangements are hardwired and follow simple mechanical algorithms carried out by genes, but Levin suspected it wasn't so preordained. So he electrically scrambled the normal development of frog embryos to create tadpoles with eyes, nostrils and mouths in all the wrong places. Levin dubbed them "Picasso tadpoles," and they truly looked the part.

If the remodeling were preprogrammed, the final frog face should have been as messed up as the tadpole. Nothing in the frog's evolutionary past gave it genes for dealing with such a novel situation. But Levin watched in amazement as the eyes and mouths found their way to the right arrangement while the tadpoles morphed into frogs. The cells had an abstract goal and worked together to achieve it. "This is intelligence in action," Levin wrote, "the ability to reach a particular goal or solve a problem by undertaking new steps in the face of changing circumstances." Fused into a hive mind through bioelectricity, the cells achieved feats of bioengineering well beyond those of our best gene jockeys.

Some of the most intense interest in Levin's work has come from the fields of artificial intelligence and robotics, which see in basal cognition a way to address some core weaknesses. For all their remarkable prowess in manipulating language or playing games with well-defined rules, AIs still struggle immensely to understand the physical world. They can churn out sonnets in the style of Shakespeare, but ask them how to walk or to predict how a ball will roll down a hill, and they are clueless.

According to Bongard, that's because these AIs are, in a sense, too heady. "If you play with these AIs, you can start to see where the cracks are. And they tend to be around things like common sense and cause and effect, which points toward why you need a body. If you have a body, you can learn about cause and effect because you can *cause effects*. But these AI systems can't learn about the world by poking at it."

Bongard is at the vanguard of the "embodied cognition" movement, which seeks to design robots that learn about the world by monitoring the way their form interacts with it. For an example of embodied cognition in action, he says, look no further than his one-and-a-half- year-old child, "who is probably destroying the kitchen right now. That's what toddlers do. They poke the world, literally and metaphorically, and then watch how the world pushes back. It's relentless."

Bongard's lab uses AI programs to design robots out of flexible, LEGO-like cubes that he calls "*Minecraft* for robotics." The cubes act like blocky muscle, allowing the robots to move their bodies like caterpillars. The AI-designed robots learn by trial and error, adding and subtracting cubes and "evolving" into more mobile forms as the worst designs get eliminated.

In 2020 Bongard's AI discovered how to make robots walk. That accomplishment inspired Levin's lab to use microsurgery to remove live skin stem cells from an African clawed frog and nudge them together in water. The cells fused into a lump the size of a sesame seed and acted as a unit. Skin cells have cilia, tiny hairs that typically hold a layer of protective mucus on the surface of an adult frog, but these creations used their cilia like oars, rowing through their new world. They navigated mazes and even closed up wounds when injured. Freed from their confined existence in a biological cubicle, they became something new and made

Plants use bioelectricity to communicate and take action. If you brush a sensory hair on a Venus flytrap (*right*), and the flytrap is wired to a touch-me-not plant (*left*), leaves on the touch-me-not will fold and wilt.

the best of their situation. They definitely weren't frogs, despite sharing the identical genome. But because the cells originally came from frogs of the genus *Xenopus,* Levin and Bongard nicknamed the things "xenobots." In 2023 they showed similar feats could be achieved by pieces of another species: human lung cells. Clumps of the human cells self-assembled and moved around in specific ways. The Tufts team named them "anthrobots."

To Levin, the xenobots and anthrobots are another sign that we need to rethink the way cognition plays out in the actual world. "Typically when you ask about a given living thing, you ask, 'Why does it have the shape it has? Why does it have the behaviors it has?' And the standard answer is evolution, of course. For eons it was selected for. Well, guess what? There have never been any xenobots. There's never been any pressure to be a good xenobot. So why do these things do what they do within 24 hours of finding themselves in the world? I think it's because evolution does not produce specific solutions to specific problems. It produces problem-solving machines."

Xenobots and anthrobots are, of course, quite limited in their capabilities, but perhaps they provide a window into how intelligence might naturally scale up when individual units with certain goals and needs come together to collaborate. Levin sees this innate tendency toward innovation as one of the driving forces of evolution, pushing the world toward a state of, as Charles Darwin might have put it, endless forms most beautiful. "We don't really have a good vocabulary for it yet," he says, "but I honestly believe that the future of all this is going to look more like psychiatry talk than chemistry talk. We're going to end up having a calculus of pressures and memories and attractions."

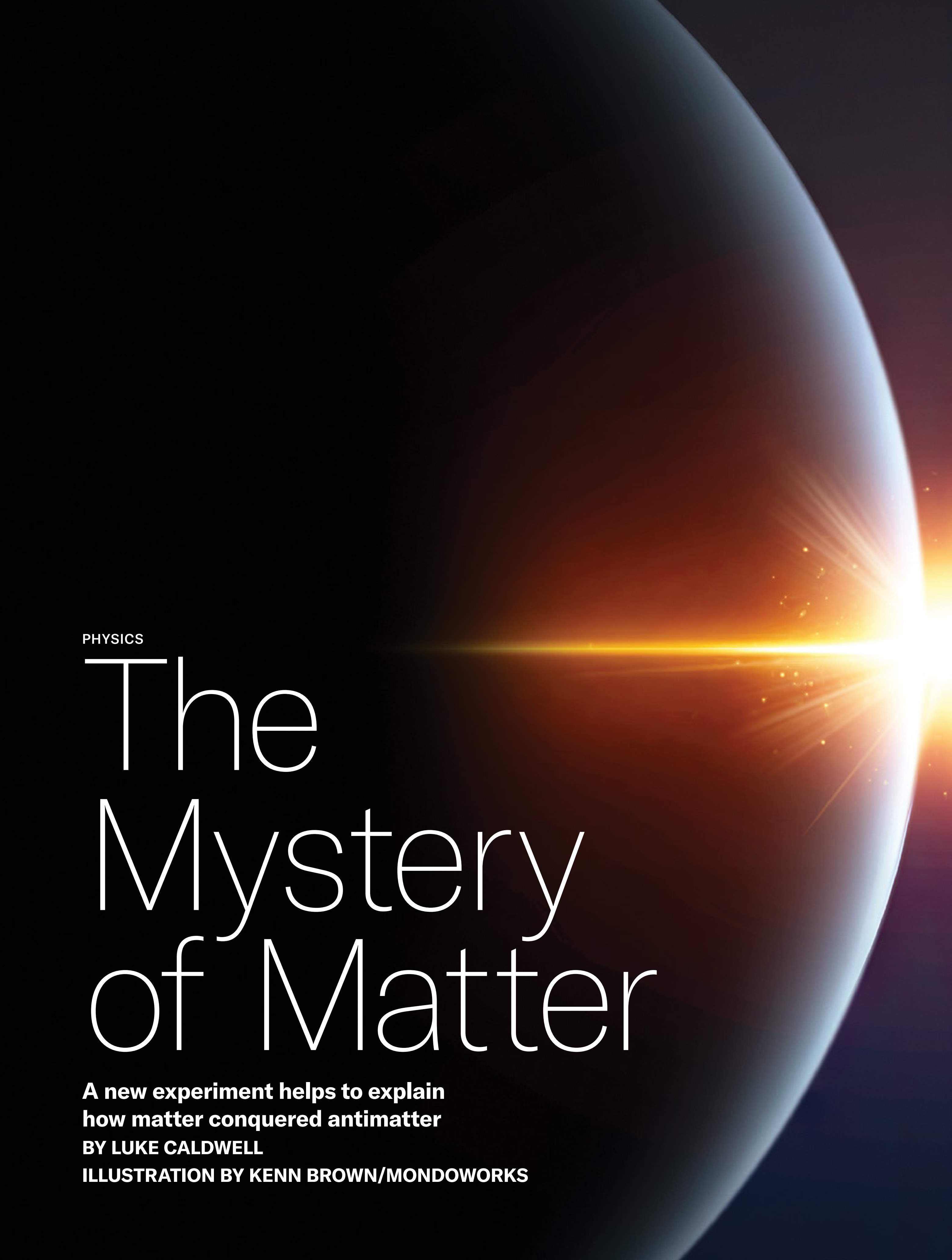
LEVIN HOPES THIS VISION will help us overcome our struggle to acknowledge minds that come in packages bearing little resemblance to our own, whether they are made of slime or silicon. For Adelaide's Lyon, recognizing that kinship is the real promise of basal cognition. "We think we are the crown of creation," she says. "But if we start realizing that we have a whole lot more in common with the blades of grass and the bacteria in our stomachs—that we are related at a really, really deep level—it changes the entire paradigm of what it is to be a human being on this planet."

Indeed, the very act of living is by default a cognitive state, Lyon says. Every cell needs to be constantly evaluating its surroundings, making decisions about what to let in and what to keep out and planning its next steps. Cognition didn't arrive later in evolution. It's what made life possible.

"Everything you see that's alive is doing this amazing thing," Lyon points out. "If an airplane could do that, it would be bringing in its fuel and raw materials from the outside world while manufacturing not just its components but also the machines it needs to make those components and doing repairs, *all while it's flying!* What we do is nothing short of a miracle."

FROM OUR ARCHIVES

New Clues about the Origins of Biological Intelligence. Rafael Yuste and Michael Levin; ScientificAmerican.com, December 11, 2021. ScientificAmerican.com/archive



PHYSICS

The Mystery of Matter

A new experiment helps to explain how matter conquered antimatter

BY LUKE CALDWELL

ILLUSTRATION BY KENN BROWN/MONDOWORKS

THE UNIVERSE SHOULDN'T BE HERE. Everything scientists know about particle physics, summed up in a theory called the Standard Model, suggests that the big bang should have created equal quantities of matter and antimatter. A mirror version of matter, antimatter consists of partner particles for all the regular particles we know of, equal in every way but with opposite charge. When matter and antimatter particles collide, they destroy one another, so the mass created when the universe was born should have been completely wiped out, leaving an empty, featureless cosmos containing only light. That there was enough leftover matter after this great annihilation to form galaxies, stars, planets and even us but almost no antimatter is known as the matter-antimatter imbalance. This existential anomaly is one of the great outstanding mysteries of modern physics.

Physicists have concocted many hypotheses to explain this mismatch, but we don't know which, if any, are true. Some of them seek to offer matter the upper hand by introducing new particles that decay, producing more matter than antimatter in the process, or that interact differently with matter and antimatter. And some of these proposals include side effects that scientists can hope to detect, thereby providing evidence for the theories. One example is an exotic property of electrons called the electric dipole moment, a small difference between the center of mass of an electron and its center of charge. Such a displacement has never been detected and should be much smaller than current experiments could measure. But many proposed extensions to the Standard Model that seek to explain the matter-antimatter imbalance predict much larger values for the electric dipole moment.

Recently I worked with colleagues to attempt to detect this signal. Our laboratory, nestled against the foothills of the Rocky Mountains at JILA, a research institute of the University of Colorado Boulder, took a different route than usual experiments. We pioneered a new strategy that allowed us to make the most precise measurement yet of the electric dipole moment.

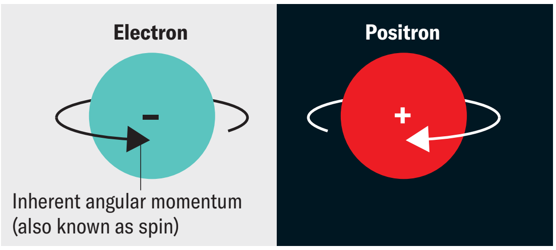
Luke Caldwell is a lecturer at University College London where his work focuses on using tabletop experiments to test the fundamental laws of physics.

TO UNDERSTAND WHAT we were looking for, imagine any simple physics experiment. Now picture repeating that experiment with all positive charges replaced by negative ones (and vice versa) and the entire apparatus arranged in the opposite direction as if reflected in a mirror. If you got an equivalent result with the mirror setup, the experiment would be said to conserve charge and parity symmetry (CP symmetry for short). In 1967 physicist Andrei Sakharov showed that this symmetry is intimately connected to the matter-antimatter imbalance. If our universe as we currently find it developed from a universe that was initially composed of equal parts matter and antimatter, something must have happened to break CP symmetry, Sakharov found. Around the same time, other researchers discovered that nature does sometimes violate CP symmetry. For instance, the weak force—responsible for radioactivity in atomic nuclei—slightly breaks this symmetry when it interacts with quarks.

Yet the instances of known CP violation in the Standard Model aren't enough to explain the matter-antimatter imbalance. We must find new, undiscovered physics phenomena that don't conserve CP symmetry to solve the mystery.

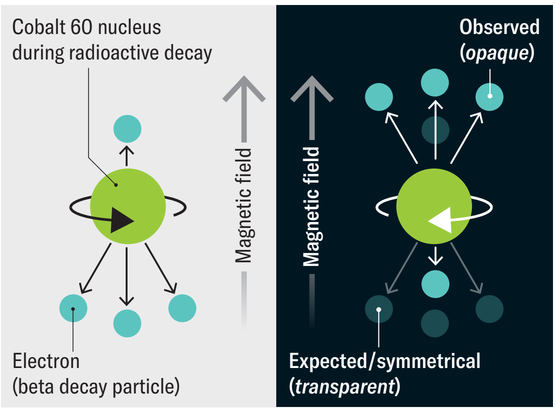
Conservation of Charge and Parity (CP) Symmetry

This state is achieved if the experimental results remain the same when all charges are reversed, and the particles are reflected, as if seen in a mirror.



Known Parity Violation

In 1956 Chien-Shiung Wu showed that—unlike like much of the rest of the universe—interacting particles inside an atom's nucleus do not always behave symmetrically.

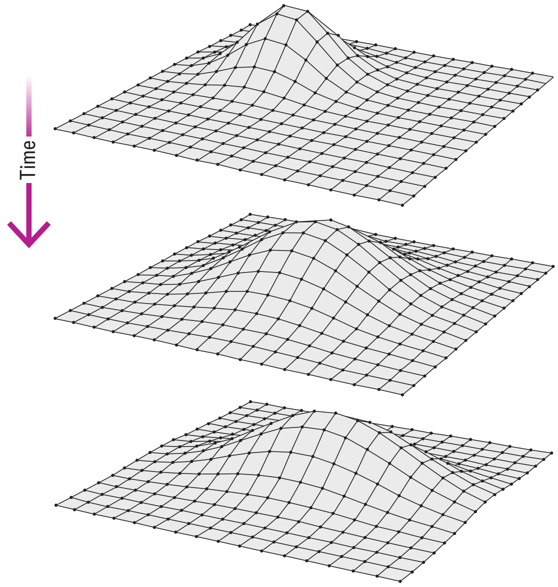


That's where our experiment comes in. It searches for evidence of new particles in the universe by looking for subtle effects on known particles. These effects occur because of the nature of the Standard Model, which is a type of quantum field theory. In quantum field theories, the basic building blocks of the universe are fields, not particles. There is a field for each of the particles in nature, from common particles such as electrons and photons to their more exotic cousins such as muons and gluons. You can imagine two-dimensional analogues of these fields as huge, flexible sheets that extend through all of space, supporting ripples like the surface of a lake does. In a quantum field, ripples can occur only in certain discrete sizes. The smallest possible ripple in a given field is what we call a particle; positive ripples in the field are matter particles, and negative ripples in the field are antimatter particles.

The amount of energy it takes to create the smallest possible ripple depends on the stiffness of the stretchy sheet; this minimum amount of energy is the rest mass of the associated particle. The different fields are linked together—or "coupled"—so that a ripple in one field disturbs the connected fields. For example, an oscillating ripple in the electron field creates accompanying ripples in the electromagnetic field corresponding to photons, a phenomenon we make good use of in everyday devices such as radio antennae and mobile phones.

2-Dimensional Representation of a Simple Field

The particle is represented by ripples, not by discrete points within the field.



Physicists' most successful tools for discovering new fields, and the particles associated with them, have historically been particle colliders. These machines direct two particles—protons, for example—to fly toward each other at high speeds. When the particles (ripples) crash into each other like two water waves meeting on a beach, their violent interactions can cause some of their energy to be carried off as ripples in other fields. If the energy of their collision is exactly equal to the energy needed to create a ripple in one of the other fields they are coupled to, we get what's called resonant enhancement, which greatly increases the probability of a new particle being created. Such collision resonances were used to discover many of the fields we know about—including the most recently confirmed piece of the Standard Model, the Higgs field, with its associated particle, the Higgs boson.

The world's most powerful accelerator, the 27-kilometer ring of the Large Hadron Collider (LHC) near Geneva, is now operating at the highest collision energies it was designed for, but so far it hasn't discovered any other new fields. If undiscovered fields exist, either their mass is higher than the LHC can reach or their coupling to the fields of the Standard Model is too weak for the LHC to create them. A new particle collider capable of reaching much higher energies is likely to cost many tens of billions of dollars, and as a result, even agreeing on whether and

Graphics by Jen Christiansen

It was surprising to me that, in certain cases, tabletop tests can answer questions about fundamental physics that the world's most expensive experiments cannot.

how it should be funded is likely to take many years.

Luckily, there is another way to detect new particles and fields, which involves making precision measurements. As mentioned earlier, because the fields of the Standard Model are coupled, a ripple corresponding to a particle in one field always causes disturbances in other fields. For example, an electron—a ripple in the electron field—disturbs the electromagnetic field around it. This disturbance in the electromagnetic field in turn disturbs the other fields that are coupled to it, and so on, eventually including all known fields of the Standard Model. What we call an electron is actually a composite excitation of all these fields, like a large water wave causing disturbances in the air above it. The effect is sometimes referred to as the electron being surrounded by a cloud of "virtual particles."

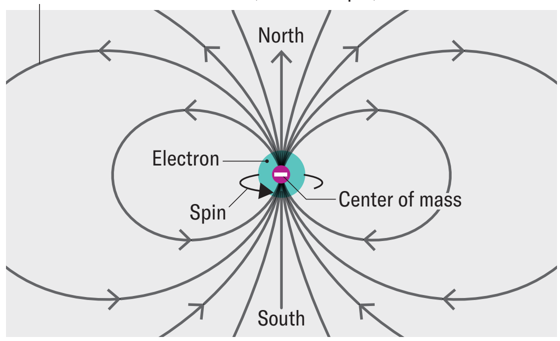
These accompanying disturbances of the other fields affect many of the electron's properties, so by carefully measuring these properties, we can infer the presence of any undiscovered fields that are coupled to the electron. If those fields are associated with heavier particles, they are stiffer and therefore less disturbed by the rippling electron field—meaning they cause less of a change to the electron's properties. Measuring the effects of fields with particles of higher and higher masses thus requires measurements with greater and greater precision.

One difficulty of this approach is that often the kind of change we're looking for is overshadowed by modifications from fields of the Standard Model. For example, an electron has a magnetic field similar to a tiny bar magnet. The strength of this field is the electron's magnetic dipole moment, and it has been measured to very high precision. Its value is determined mostly by the magnetic moment of the bare electron field; the largest changes arise from the electromagnetic field, and they can be calculated with astonishing precision. At the level of precision achieved by current experiments, however, the exact value of the Standard Model coupling between an electron and electromagnetic fields is not exactly known—there is some discrepancy in the measured values from different experiments. Even if this problem is resolved, the tiny effects of interactions with quark fields and the strong force will be important. These effects can be incredibly complex and difficult to calculate, making our search for similar-sized (or smaller) effects from exotic physics challenging.

A nice way around this problem is to find a property that is zero (or very, very small) in the Standard Model. According to the theory, there should be only a minuscule separation between an electron's center of mass and center of charge—in other words, its electric dipole moment. The electric dipole moment of an electron (eEDM), the electric counterpart of the magnetic moment, can essentially be caused only by interactions that violate CP symmetry. The CP violation contained within the Standard Model is exceedingly small, well below current experimental sensitivity. In contrast, many extensions to the Standard Model, proposed to help explain the matter-antimatter imbalance, predict eEDMs many orders of magnitude larger and within reach of near-term experiments.

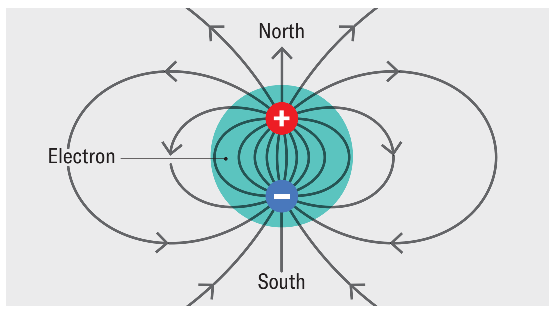
Magnetic Dipole

A magnetic field is generated by the inherent angular momentum of the electron (so-called spin).



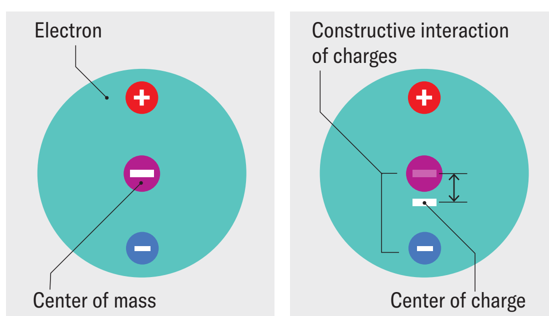
Electric Dipole

An electromagnetic dipole may also be present as a result of an offset in charges within the electron.



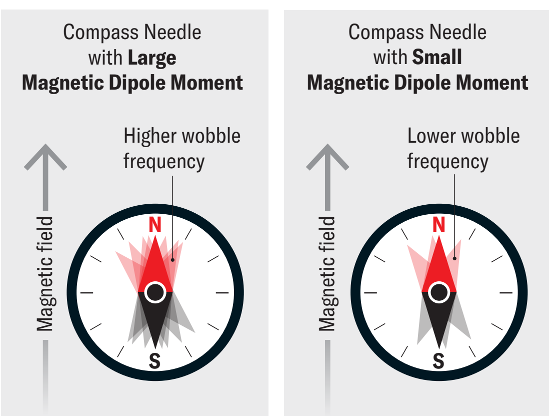
Electric Dipole Moment

If an electric dipole is present, the center of charge is shifted away from the center of mass by a theoretically measurable amount.



I remember being extremely excited reading about these ideas for the first time as a physics student. In contrast to the enormous infrastructure and huge collaborations involved in running particle colliders like the LHC, experiments to measure everyday particles such as an electron can often fit on a (admittedly large) table in a conventional university laboratory and be handled by a few scientists. It was surprising to me that, in certain cases, these tests can answer questions about fundamental physics that the world's most expensive experiments cannot. The tabletop projects also seemed much better suited to my personality. In large collaborations, individual roles are usually highly specialized; in contrast, running a tabletop experiment requires everyone to take a holistic view of the entire apparatus. We must be generalists, garnering passable knowledge of many different disciplines and technologies, from electronics and computer programming to lasers and vacuum chambers. I love this kind of variety and the chance to do something big with something relatively small.

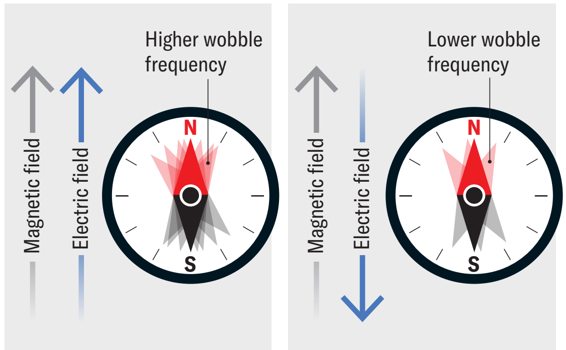
TO SAY AN ELECTRON has a nonzero electric dipole moment is equivalent to saying it has a preferred orientation in an electric field—just as the needle of a compass (which has a magnetic dipole moment) has a preferred orientation in Earth's magnetic field. If a compass needle is briefly nudged, it will wobble backward and forward around magnetic north. The frequency of this wobble is proportional to both the strength of the magnetic field and the size of the magnetic dipole moment of the needle.



As a result, if you measure the frequency of the wobble in a known magnetic field, you will know the size of the needle's magnetic dipole moment. If the needle also has an EDM, perhaps because we charged up one end of it somehow, we can measure its size by simultaneously applying an electric field. When the electric field is parallel with the magnetic field, the needle will wobble with a slightly increased frequency; when the electric field is pointing in the opposite direction, the wobble frequency will decrease. The difference between these two frequencies tells us the size of the needle's EDM. We can search for the electron's EDM in precisely the same way, first placing the particle in a magnetic field and then measuring the shift in its wobble frequency when we apply an electric field parallel and then antiparallel to that magnetic field.

Determining Size of an Electric Dipole Moment

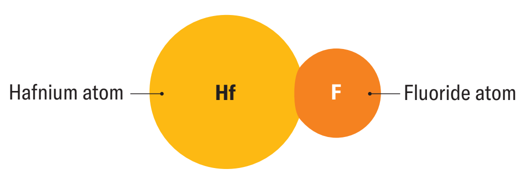
Wobble frequency can also be influenced by the relative direction of external magnetic and electric fields.



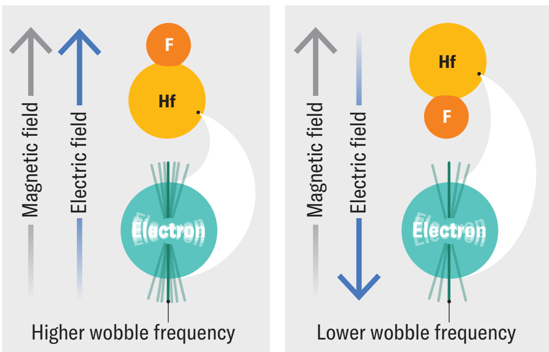
The size of the electric dipole moment can be calculated using the wobble frequency difference between scenarios.

We know the eEDM must be very tiny, if it exists at all, so we know we are looking for an extremely tiny shift in the wobble frequency. We can boost the signal by applying a larger electric field. A powerful way to do this is to use electrons confined inside heavy atoms and molecules. You might think that an electron in an atom or molecule wouldn't experience any electric field, or else it would fly away. This is true, however, only if you ignore Einstein's special theory of relativity. When relativity is taken into account, it turns out that in heavy atoms, where relativistic effects are most important because electrons move at close to the speed of light near the highly charged nucleus, the effective electric fields acting on the electron can be tremendous—around a million times larger than the strongest fields we can generate in a lab. To take advantage of this fantastically large field for our measurement, we need apply only enough of an electric field in the lab to orient the atom or molecule. This work turns out to be much easier with molecules, so for the past decade or so all the leading experiments of this type have used electrons in heavy molecules made of two atoms. Our experiment uses hafnium monofluoride molecules because hafnium, with 72 protons in its nucleus, is one of the heaviest metals in the periodic table that isn't radioactive.

Hafnium Monofluoride Molecule

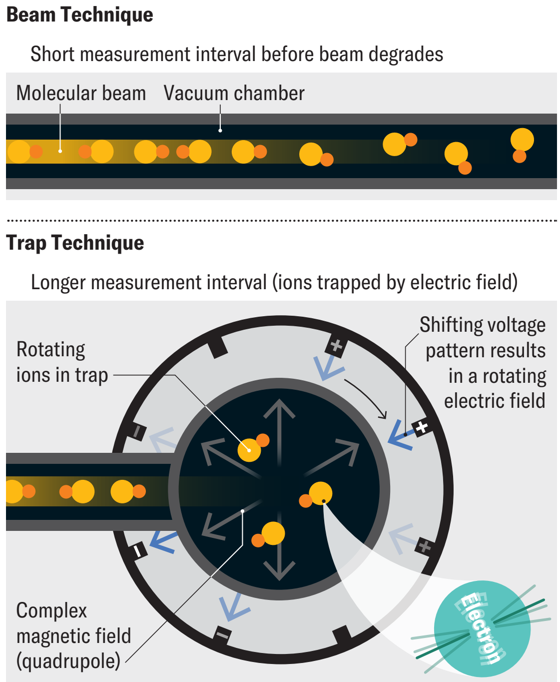


Even with this enormous electric field, the change in the wobble frequency of the electron that we might expect from a realistically sized EDM is still very tiny, corresponding to about one extra wobble every seven hours or so. To detect such a minuscule change, we need to measure the two frequencies, with the electric field parallel and then opposite to the direction of the magnetic field, extremely precisely. The longer we monitor a frequency, the more wobbles we can measure and therefore the more precise we can make our measurement.



Our timing is limited by how long our molecules last. For these kinds of experiments, we must use molecules that have free, unpaired electrons, which makes them highly reactive—the electrons are eager to bond with any other atoms they encounter. We have to keep our molecules in vacuum chambers where they don't come into contact with other particles or the walls of the chamber. Previous experiments have used beams of molecules traveling at hundreds of meters per second down a long vacuum chamber, with researchers observing the molecules in free flight. In this setup, the measurement time is limited by how long the beam of molecules can travel before it starts spreading out too much and the signal is lost. Typically this happens within about a meter, or around one millisecond.

For our experiment, we wanted to be able to observe the electrons for longer. We decided to use trapped molecular ions—charged molecules—which we held in position with electric fields. Trapping molecular ions this way isn't new, but no one had previously thought such traps would work for an electric dipole measurement on electrons. These measurements require that we expose our molecules to electric fields, and if the molecules are charged ions, the electric fields should cause them to accelerate away. But the head of our lab, Eric Cornell, had an exciting insight: he suggested that we rotate the electric field fast enough that, instead of flying away, the ions just trace out small circles within the trap. This method let us measure our molecules for three seconds—a great improvement on previous experiments. Our measurement time was limited mainly by the time it took for our molecules to decay into lower-energy states.



Our ion trap technique does have a drawback, though. Because we could trap only so many ions at once, our experiment measured many fewer electrons in each run than typical beam experiments. We were able to observe a few hundred electrons per shot. Over two months of long days in the lab, we measured more than 100 million electrons in total.

Gathering the data set was the quick part. The real challenge of a precision experiment is the time spent looking for systematic errors—ways we might convince ourselves we had measured an eEDM when in fact we had not. Precision-measurement scientists take this job very seriously; no one wants to declare they have discovered new particles only to later find out they had only precisely measured a tiny flaw in their apparatus or method. We spent about two years hunting for and understanding such flaws.

An important source of errors in EDM experiments is the level of control over the magnetic field. Recall that we are looking for a difference in the wobble frequency of an electron in a magnetic field when an electric field is applied parallel to and then opposing the direction of that magnetic field. The problem is that the wobble frequency depends on the strength of the magnetic field. If that field drifts slightly between the two measurements, the result will look like an EDM. To address this possibility, we found a way to do both electric field measurements simultaneously. We take a cloud of molecules and prepare half with their internal electric field aligned with the external magnetic field and half with their internal electric field anti-aligned. We then measure the wobbles of electrons in both groups simultaneously, and because both are in the same trap at the same time, they experience the same magnetic fields to very high precision.

Another source of systematic error is experimenter bias. All scientists are human beings and, despite our best efforts, can be biased in our thoughts and decisions. This fallibility can potentially affect the results of experiments. In the past it has caused researchers to subconsciously try to match the results of previous experiments. A well-studied example is in measurements of the speed of light. In the late 19th century attempts to determine this constant overestimated it significantly. Later, measurements tended to underestimate the value, leading some physicists to suggest that the speed of light was changing. But in fact, researchers were probably unconsciously steering their data to fit better with previous values, even though those turned out to be inaccurate. It wasn't until experimenters had a much better grasp on the true size of their errors that the various measurements converged on what we now think is the correct value.

To avoid this issue, many modern precision-measurement experiments take data "blinded." In our case, after each run of the experiment, we programmed our computer to add a randomly generated number—the "blind"—to our measurements and store it in an encrypted file. Only after we had gathered all our data, finished our statistical analysis and even mostly written the paper did we have the computer subtract the blind to reveal our true result.

The day of the unveiling was a nerve-racking one. After years of hard work, our team gathered to find out the final result together. I had written a computer program to generate a bingo-style card with 64 plausible numbers, only one of which was the true result. The other numbers varied from "consistent with zero" to "a very significant discovery." Slowly, all the fake answers disappeared from the screen one by one. It's a bit weird to have years of your professional life condensed into a single number, and I questioned the wisdom of amping up the stress with the bingo card. But I think it became apparent to all of us how important the blinding technique was; it was hard to know whether to be relieved or disappointed by the vanishing of a particularly large result that would have hinted at new, undiscovered particles and fields but also contradicted the results of previous experiments.

Finally, a single value remained on the screen. Our answer was consistent with zero within our calculated uncertainty. The result was also consistent with previous measurements, building confidence in them as a collective, and it improved on the best precision by a factor of two. So far, it seems, we have no evidence that the electron has an EDM.

Though perhaps not as exciting as a nonzero value, our new upper limit on the possible size of the eEDM has substantial consequences. If we assume that any new CP-violating field couples to electrons with a strength similar to that of the electromagnetic field (a middling coupling strength in the Standard Model, between those of the fields representing the weak and strong forces), our measurement means that the mass of its associated particle must be more than roughly 40 tera electron volts. This limit would place it far beyond the highest mass of a particle that could be directly discovered at the LHC.

THIS RESULT, AND THOSE of other recent eEDM measurements, is surprising to many who expected new fields to exist below this energy scale. One possible explanation is that the fields couple to the Standard Model in such a way that their contribution to the eEDM is only indirect and therefore smaller for a given mass than the estimate above assumes. Researchers might be able to confirm this possibility by making complementary measurements of EDMs in other particles built from quarks where the coupling is likely to be different. Such measurements are currently underway for neutrons and for mercury nuclei, and many more are planned.

Another possibility is that the new fields are at just slightly higher energies or smaller couplings, out of reach of our experiment but accessible to the next generation of eEDM measurements. I expect the next decade or so to see significant precision improvements. At JILA, we're already working on using a different molecule, thorium fluoride, which has a stronger internal electric field, to increase the observation time still further, perhaps out to 20 seconds. We're also planning to partially address our disadvantage in the number of molecules we can trap by running many copies of the experiment in parallel with tens of separate traps in one long vacuum chamber.

And we expect to see major advances from the latest iteration of the world's best molecular beam experiment, the ACME III project (for "advanced cold molecule EDM"), based at Northwestern University, where scientists are improving the focus of their molecular beam to extend their measurement time. Simultaneously, other physicists are working on ways to trap neutral molecules using laser-cooling techniques. This method could potentially combine the advantages of long measurement times and large numbers of electrons. And an ambitious plan by researchers in Canada aims to study molecules confined inside a solid crystal of frozen noble gas. This technique could enable measurements of colossal numbers of electrons in each shot, but it remains to be seen how the fields from other nearby atoms in the solid will affect the measurement.

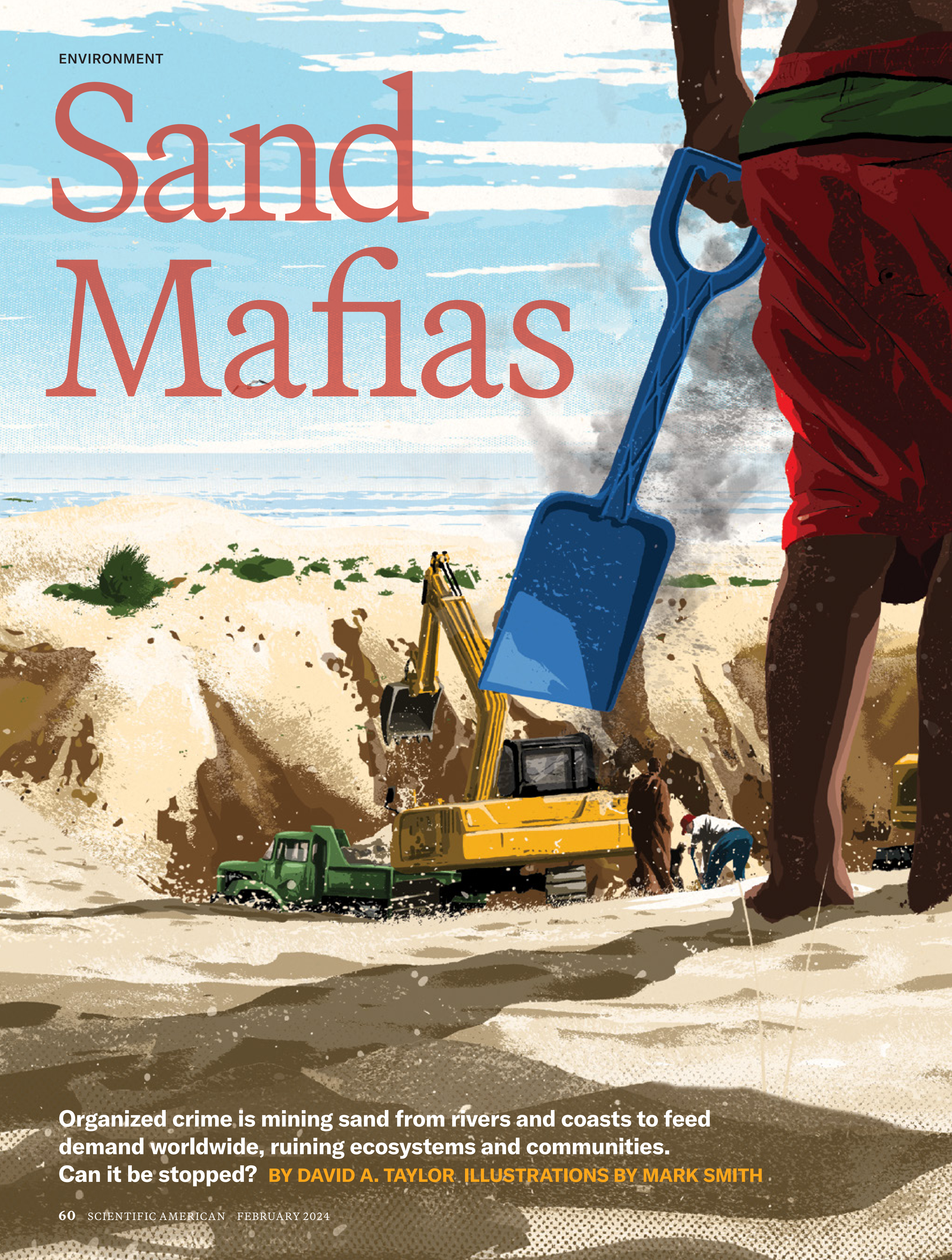
Ultimately, we hope to either detect an electric dipole moment in an electron or limit its possible size enough to effectively rule out the types of fields and particles scientists have envisioned to explain our antimatter mystery. We know there must be some reason out there for the universe of matter we live in to be the way it is—the question is how long it will take us to discover it. ■

FROM OUR ARCHIVES

The Deepest Recesses of the Atom. Abhay Deshpande and Rikutaro Yoshida; June 2019. ScientificAmerican.com/archive

ENVIRONMENT

Sand Mafias



Organized crime is mining sand from rivers and coasts to feed demand worldwide, ruining ecosystems and communities. Can it be stopped? By David A. Taylor Illustrations by Mark Smith

TRANSNATIONAL SECURITY INVESTIGATOR Abdelkader Abderrahmane set out from the Moroccan city of Kenitra with two research assistants to inspect sand-mining sites on the Atlantic Ocean coast. They drove across the dry, flat terrain for six kilometers, the last stretch on a rutted dirt road that had them crawling in low gear, windows closed against the hot dust. The beach dunes where they were headed lay beyond a rise. As they approached, a man wearing a gendarme cap suddenly appeared to their right, speeding toward them on an all-terrain vehicle. With angry gestures, he forced them to a stop. "Why are you here?!" he demanded. "There's nowhere to go." One assistant said they just wanted to visit the beach and the nearby tourist camp. The gendarme shook his head: no further.

They turned around and began to creep back down the rough road, but as soon as the gendarme was out of sight they turned off and snuck along a hidden side of the ridge. About 400 meters further they stopped and cut the engine. Abderrahmane walked quietly to the crest of the bluff to peer down, keeping low to avoid being seen. Despite all his research into illegal sand mines, he was unprepared for the scene below. Half a dozen dump trucks scattered across a deeply pitted moonscape were filled high with brown sand. Just beyond lay the light blue sea. Abderrahmane was stunned by the "major disfiguration" of the dunes, he told me later on a video call. "It was a shock."

Part of his shock came from the sight of desecrated nature, but part came from seeing the brazenness of trucks hauling sand in full daylight. "You cannot illegally mine sand in daylight if you don't have people helping you," he says—people in high places. "Big companies are being protected, perhaps by ministers or deputy ministers or whoever. It's a whole system." Everyone in the sand-trafficking market "benefits from it, from top to bottom."

For the past 15 years the slender, bespectacled Abderrahmane has studied environmental trade and crime for the Institute for Security Studies (ISS), an African research and policy advisory organization based in South Africa. ISS papers showed how environmental degradation can fuel tensions among people and compromise security. But until a few years ago Abderrahmane had never heard of sand trafficking. He had been in Mali doing fieldwork on the drug trade when a source noted that most cannabis in Mali came from Morocco and that sand trafficking was also a major market in that country, with drug traffickers involved. "I think that when you talk about sand trafficking, most people would not believe it," Abderrahmane says. "Me included. Now I do."

Very few people are looking closely at the illegal sand system or calling for changes, however, because sand is a mundane resource. Yet sand mining is the world's largest extraction industry because sand is a main ingredient in concrete, and the global construction industry has been soaring for decades. Every year the world uses up to 50 billion metric tons of sand, according to a United Nations Environment Program report. The only natural resource more widely consumed is water. A 2022 study by researchers at the University of Amsterdam concluded that we are dredging river sand at rates that far outstrip nature's ability to replace it, so much so that the world could run out of construction-grade sand by 2050. The U.N. report confirms that sand mining at current rates is unsustainable.

The greatest demand comes from China, which used more cement in three years (6.6 gigatons from 2011 through 2013) than the U.S. used in the entire 20th century (4.5 gigatons), notes Vince Beiser, author of

David A. Taylor has written for the *Washington Post* magazine, *Smithsonian, Mother Jones,* and others. His latest book is *Cork Wars: Intrigue and Industry in World War II* (Johns Hopkins University Press, 2018).

The World in a Grain. Most sand gets used in the country where it is mined, but with some national supplies dwindling, imports reached $1.9 billion in 2018, according to Harvard's Atlas of Economic Complexity.

Companies large and small dredge up sand from waterways and the ocean floor and transport it to wholesalers, construction firms and retailers. Even the legal sand trade is hard to track. Two experts estimate the global market at about $100 billion a year, yet the U.S. Geological Survey Mineral Commodity Summaries indicates the value could be as high as $785 billion. Sand in riverbeds, lake beds and shorelines is the best for construction, but scarcity opens the market to less suitable sand from beaches and dunes, much of it scraped illegally and cheaply. With a shortage looming and prices rising, sand from Moroccan beaches and dunes is sold inside the country and is also shipped abroad, using organized crime's extensive transport networks, Abderrahmane has found. More than half of Morocco's sand is illegally mined, he says.

Luis Fernando Ramadon, a federal police specialist in Brazil who studies extractive industries, estimates that the global illegal sand trade ranges from $200 billion to $350 billion a year—more than illegal logging, gold mining and fishing combined. Buyers rarely check the provenance of sand; legal and black market sand look identical. Illegal mining rarely draws heat from law enforcement because it looks like legitimate mining—trucks, backhoes and shovels—there's no property owner lodging complaints, and officials may be profiting. For crime syndicates, it's easy money.

The environmental impacts are substantial. Dredging rivers destroys estuaries and habitats and exacerbates flooding. Scraping coastal ecosystems churns up vegetation, soil and seabeds and disrupts marine life. In some countries, illegal mining makes up a large portion of the total activity, and its environmental impacts are often worse than those of legitimate operators, Beiser says, all to build cities on the cheap.

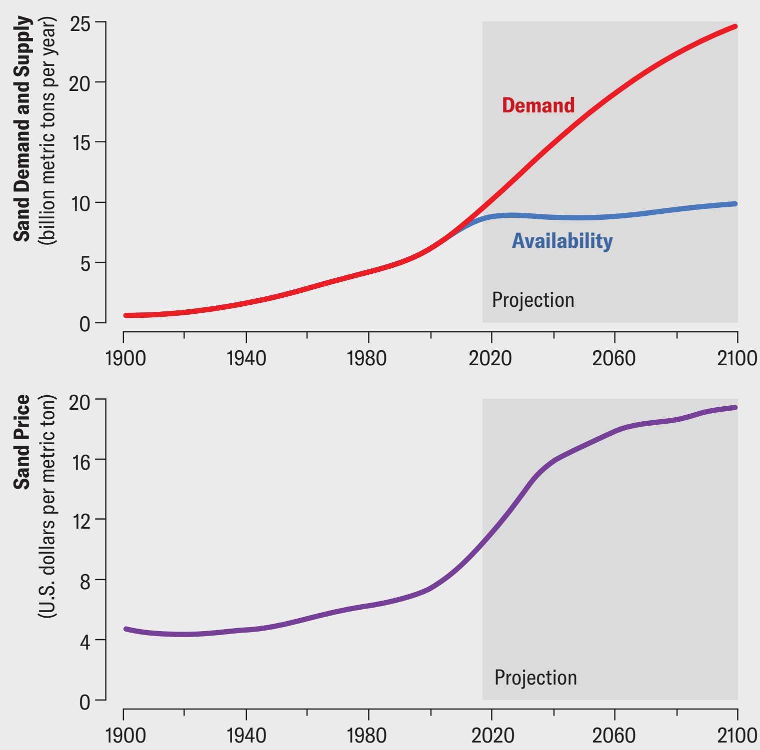
Questionable mining happens worldwide. In the early 1990s in San Diego County, California, officials stopped mining from the San Luis Rey River, only to see operators move across the border into Baja California to plunder riverbeds there. Until a few years ago, a mine north of Monterey, Calif., operated by Cemex, a global construction company, was pulling more than 270,000 cubic meters of sand every year from the beach, operating in a legal gray zone. That was the last beach mine in the U.S., shut down in 2020 by grassroots pressure. Mining in rivers and deltas, however, is still going strong throughout the U.S., not all of it legal.

SAND IS ANY HARD, granular material—stones, shells, whatever—between 0.0625 and two millimeters in diameter. Fine-quality sand is used in glass, and still-finer grades appear in solar panels and silicon chips for electronics. Desert sand typically consists of grains rounded like tiny marbles from constant weathering. The best sand for construction, however, has angular grains, which helps concrete mixtures bind. River sand is preferable to coastal sand, partly because coastal sand has to be washed free of salt. But coastal sand does get used, especially when builders take shortcuts, leading to buildings that have shorter life spans and pose greater risks for inhabitants. Such shortcuts worsened the damage from the disastrous February 2023 earthquake that shook Turkey and Syria, says Mette Bendixen, a physical geographer at McGill University who has investigated the effects of sand mining since 2017.

I was first alerted to sand mafias by Louise Shelley, who leads the Terrorism, Transnational Crime and Corruption Center at George Mason University. Shelley realized sand mining could be a natural evolution of organized crime when, five years ago, she was a guest at a NATO lunch conference held near the Pentagon. A top NATO official approached her to talk about illegal fishing off West Africa, saying it posed a serious threat to European and NATO security. They talked about how the low threshold for entry into an environmental crime such as wildlife poaching can draw criminal rings and then lead them into other types of organized environmental crime, such as illegal logging. Sand mining was another case in point. Shelley says in northwestern Africa there is a conflu-

The Growing Demand for Sand

The market for sand—a prime ingredient in concrete, glass and electronic circuits—has increased steadily during a century-long global construction boom. Demand is projected to rise sharply in the coming decades, outstripping the capacity of producers and perhaps even nature's ability to generate new sand, pushing prices much higher.

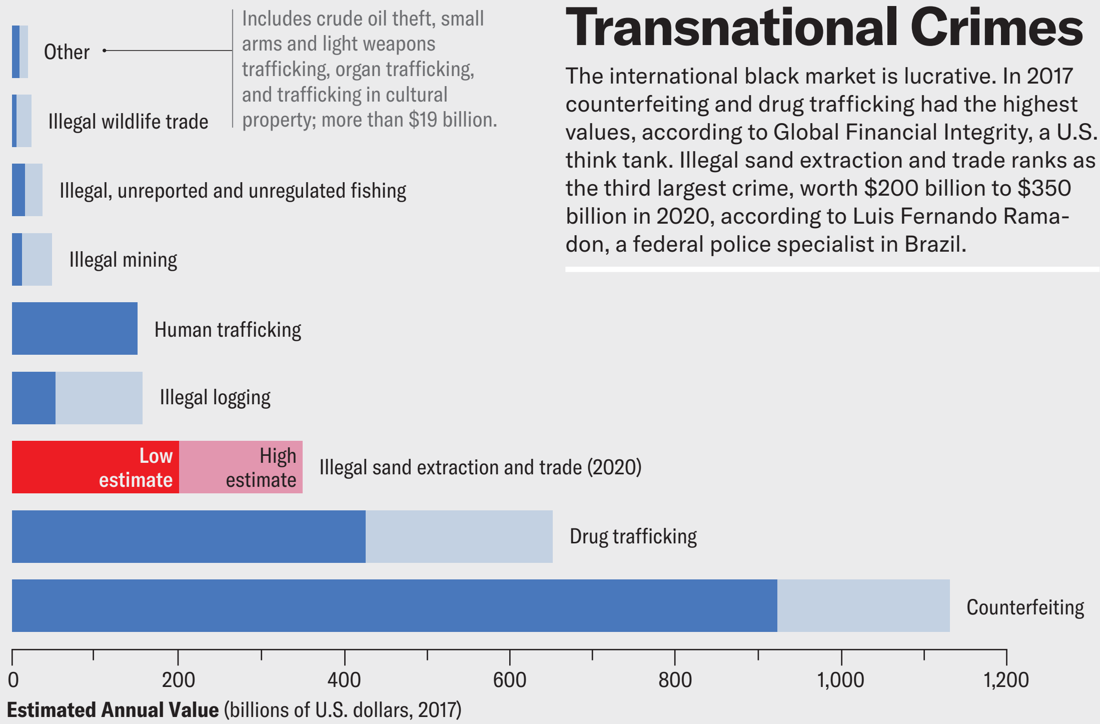


Source: "A Simple System Dynamics Model for the Global Production Rate of Sand, Gravel, Crushed Rock and Stone, Market Prices and Long-Term Supply Embedded into the WORLD6 Model," by Harald U. Sverdrup et al., in *BioPhysical Economics and Resource Quality*, Vol. 2; May 2017 (data)

Graphics by John Knight

Transnational Crimes

The international black market is lucrative. In 2017 counterfeiting and drug trafficking had the highest values, according to Global Financial Integrity, a U.S. think tank. Illegal sand extraction and trade ranks as the third largest crime, worth \$200 billion to \$350 billion in 2020, according to Luis Fernando Ramadon, a federal police specialist in Brazil.



Sources: *Transnational Crime and the Developing World*, by Channing May, Global Financial Integrity, March 2017 (*crime data*); "The Global Estimated Value of Illegal Sand Extraction," by Luis Fernando Ramadon, SandStories.org (*sand extraction estimate*)

ence of trafficking factors: the region offers entry to European markets, and its mosaic of fragile governments, terrorist groups and corrupt international corporations makes it vulnerable.

In addition to social instability, Shelley is concerned about sand mining's "devastating environmental impacts." Stripping away sand removes nature's physical system for holding water, with huge effects for people's way of life. River sand acts like a sponge, helping to replenish the entire watershed after dry spells; if too much sand is removed, natural replenishment can no longer sustain the river, which aggravates water supply for people and leads to loss of vegetation and wildlife. Harvesting has removed so much sand from Asia's Mekong Delta that the river system is drying up.

Removing sand from coasts makes land that already faces sea-level rise even more exposed. Abderrahmane saw this in Morocco when he drove north from Rabat to Larache, known as "the balcony of the Atlantic." The town, which looks out over 50-meter-high cliffs toward the sea, is a hub of Morocco's thriving fishing industry. A 2001 government document known as the Plan Azur proposed greater protection of nature in many places in the country scoured for sand, including Larache. But in his 2021 field research, Abderrahmane found that the dark sand and rock-strewn beach there was rife with mining. Teams of workers loaded up donkeys with saddle packs full of sand, leaving stony craters at the water's edge. They goaded the donkeys up footpaths torn into the soft, steep bluffs to trucks waiting above to haul the illicit material to various concrete production sites.

In Mozambique, increasingly destructive flash flooding has hit the town of Nagonha, which lies on the Indian Ocean. Elders there told Amnesty International they can't recall any comparable flooding in the past, before the Hainan Haiyu Mining Company started operations in 2011, harvesting sand and minerals such as ilmenite, titanium and zircon from the dunes. The company dumped leftover sand across a wide area, spreading it to make a level working surface, which buried existing vegetation and blocked drainage, according to an Amnesty International report.

The company's procedures failed to comply with Mozambican law, changed the flow of fresh water and are blamed for making Nagonha more vulnerable to the flash floods that have partly destroyed it, Amnesty International reported. One flood washed 48 homes into the sea, slicing a channel through the dunes, leaving nearly 300 people homeless. One man described to Amnesty International how his family's two-bedroom house vanished: "We felt the house collapsing, and we ran for our lives" as he saw their home "being dragged by the water."

SAND LOOTING is changing the hydrology of entire rivers. Halinishi Yusuf experienced this as a girl growing up in Kenya. She also witnessed mining's violent excess and eventually helped to bring it under control.

Yusuf, now studying sand mining and river systems as a Ph.D. candidate at Newcastle University in England, was born in Makueni County, southeast of Nairobi. As a girl, she carried water from the river, and like most residents, her family relied on rain-fed farming to eke out a living. But seasonal rains became erratic as a result of several interconnected climate patterns, and local farming and jobs declined. As life got harder, residents turned to harvesting sand for the construction boom in Nairobi. It was an easy form of employment because no investment was required except a shovel. Yusuf went away for high school in the early 2000s, and when she visited home, she saw trucks parked in the riverbed, loading up. Residents worked as loaders, and vendors sold food to the crews. Any river or tributary was fair game: if it gathered sand, it was exploited, and it wasn't illegal.

Yusuf didn't connect the mining to environmental damage. "It was just sand, anyway," she says about her outlook back then. And the trade pumped cash into the economy; the village "was vibrant," Yusuf told me on a video call. But damage to river systems was becoming clear. Groundwater levels were sinking; riverbeds stripped of sand didn't hold water and failed to refresh aquifers underground. Farmers already struggling couldn't irrigate their crops. Social tensions grew heated. Under Kenya's "devolution" of public services from the national government to the country's 47 counties, local agencies took responsibility for sand-harvesting licenses, often without resources to manage it. The process was unregulated and soon overwhelmed.

To try to stop the chaos, Makueni County passed a law in 2015 creating a local sand authority. But from 2015 to 2017 violence over sand wracked the area, leaving at least nine people dead and dozens injured. Even legal actors operated clandestinely, and local governments exploited permit fees, Yusuf says. "No one was frowning on this activity."

Other counties had similar conflicts, but in Makueni a small group of sand loaders changed course and became vigilantes. They realized that mining was worsening arid conditions and that only outsiders were profiting. They saw officials getting rich from bribes and construction teams hauling the county's sand wealth elsewhere. The group vowed to stop trucks no matter what it took. It imposed its ban on trucks leaving the area by torching offenders. Late one December night in 2016 two Kenyan truck drivers met a horrible death when they were parked beside the Muooni River, loading sand right out of the riverbed after midnight. The vigilantes surrounded them and set the trucks on fire. Both drivers died, burned "beyond recognition," police reported to local media.

Not all the local people wanted to stop the lucrative business, however, and two factions clashed, resulting in more deaths. The Nairobi transport network poured cash into the pro-mining faction. "The conflict was funded from outside by the sand cartel in Nairobi," Yusuf says, and law enforcement failed to intervene.

The violence and damage to the rivers peaked in mid-2017, around when Yusuf left Nairobi, where she had been working on fisheries management. She returned home to lead the Makueni County Sand Authority, which had made little headway. When applying for the job, Yusuf made her soft skills a selling point. She said she would enforce the 2015 law but noted that "there's a palatable way of making the community start appreciating why we need to do this."

When she began the job, she called a morning meeting in Muooni with local stakeholders. The village administrator and elders spread the word. Several dozen people toting plastic chairs gathered at the Muooni River, where mining was rampant, and sat in the shade. Yusuf had rehearsed her spoken Kikamba, the local language. Although she had taken part in stakeholder meetings in her fisheries job, she had never led one like this. "The entire county is watching," she thought at the time. "I have to bring it forward."

Yusuf explained to her audience how sand supports water in dry areas and how water gets replenished. She said the sand was like a sponge that made water available for them and the ecosystem. "Where there is sand, there is water," she told them. During the discussion residents became reassured that they could gain income from sand while also allowing it to recharge the water supply. Over the next five years, under Yusuf's leadership, the sand authority gained trust. It prosecuted the worst offenders and imposed strict fines on illicit mining.

Yusuf's strategy was threefold. First, she used government power to stop sand from leaving the county. The authority allowed permits only for local construction projects: no more trucks from Nairobi. Second, Yusuf continued a series of meetings with local groups at the rivers. Finally, she made her office's books public and used that transparency to show that half the revenue from licensing fees went straight to river restoration projects. People aiming to flout the controls backed off. Shady syndicates from Nairobi no longer had effective local agents in Makueni and found it easier to source their sand elsewhere.

For the first time, sand revenues produced visible local benefits. Projects ranged from "sand dams"—concrete weirs across the riverbed that catch sand pushed downstream by the rains—to "water sumps," concrete tanks sunk several meters below the riverbed, used to draw drinking water. Leaving riverbeds untouched for even one rainy season (Kenya has two rainy seasons a year) allowed upstream sediment to replenish the controlled withdrawals, according to Yusuf. The community saw that there could be a way of life beyond selling sand to outsiders.

CHANGE IS HARDER in places where local groups lack the power to manage resources. In Morocco, Abderrahmane found a wide range of people profiting from the clandestine system, from local workers to high officials. The few people who protested were intimidated. French documentarian Sophie Bontemps experienced this in 2021 when her crew was filming at dunes near El Jadida. Police arrested them for filming, Bontemps told me, interrogated them for a full day, and confiscated their equipment. That evening a military colonel working with two plainclothes officials arranged a mock trial in a hotel; near midnight they forced the crew members to sign a document in Arabic admitting they had no right to film and to erase their footage. Finally, they were released. (The team had saved the footage elsewhere.) To Bontemps, it was clear that national officials were involved in sand trafficking. Her film, *Morocco: Raiding on the Sand,* reports incidents of local protesters being threatened and beaten.

Abderrahmane was finding it difficult to clarify the range of corruption. Sand mined for nearby buildings might fly below the radar of local officials. But long-haul transport involving scores of trucks traveling long distances on a public highway could not escape notice. In Larache, he couldn't count on government support, so he took a gamble. His team posed as real-estate developers seeking contractors for a big project in Casablanca, more than 200 kilometers south. At a compound where massive reddish sand piles signaled construction supply, one of Abderrahmane's assistants entered through a corrugated metal gate late in the day, when trucks were back from deliveries. He made bidding inquiries for a fictitious building project. He was stunned by the response: bidders could mobilize hundreds of trucks and front-end loaders within a week. "That would be very easy," one man told him.

On other days the assistant directly approached drivers of sand-laden trucks parked downtown. From the driver's seat, one transporter explained that contractors could arrange night hauling with up to 250 trucks through a syndicate of firms. Once the sand got delivered, construction companies mixed trafficked sand with legal sources. The contractor's confidence that they could deliver such volumes across great distances, requiring large loads to pass at least 10 highway checkpoints, indicated multiple layers of official collusion, Abderrahmane says.

Because local people often struggle to push back against big syndicates, international pressure can push governments to prosecute traffickers. In Morocco, a strategy would likely require stronger environmental regulations, promotion of sustainable practices and transnational enforcement. An international certification system akin to the Forest Stewardship Council's process for timber sourcing is still only in the discussion phase, says Pascal Peduzzi of the U.N. Environment Program. But Abderrahmane's Moroccan sources say the government might consider action if sites were certified by the Convention on Wetlands, an international process dating back to the 1970s and observed by most U.N. member countries. A country submits a list of wetlands for accreditation, and if the international body overseeing the convention grants it, the wetlands can be monitored by an independent advisory committee to help ensure the site is preserved and not plundered. New technology might help distinguish whether sand came from a legal or illegal operation; in 2023 researchers from several universities demonstrated an optical system that can fingerprint sand grains, allowing them to be traced back to their site of origin.

Before conservationist Rachel Carson created a narrative in the 20th century for water and air pollution in *Silent Spring,* the general public had little context for seeing streams or the sky as health threats. Journalist Beiser told me he thinks a similar situation exists for sand.

George Mason's Shelley is encouraged by a new generation's energy for the problem. When we spoke, she was reading student papers about illicit environmental trade, happy that many of the students are career professionals in agencies where they can make a difference. Often it takes fresh eyes to change things, and Yusuf and Abderrahmane may inspire other people who are concerned about the environment and abuse of local communities.

More research will help build cases against crime rings. The number of sand studies presented at the American Geophysical Union's annual conference grew from two in 2018 to more than 20 in 2023, McGill's Bendixen says. That research can eventually yield better mapping of sand flows, showing hotspots and illegal activity.

Bendixen was heartened that the African Futures Conference in 2023 devoted a special session to sand extraction. "The time is running out for sand," she says. "More people from as many different angles as possible are shouting out to the world, 'We have an issue!' I think it's one of the most understudied global challenges of the 21st century." ⬣

FROM OUR ARCHIVES
Deep-Sea Dilemma. Olive Heffernan; September 2023. ScientificAmerican.com/archive

A Dignified Death

Hospices in the U.S. are increasingly run by for-profit providers, and a lack of regulation allows them to deliver abysmal end-of-life care BY THE EDITORS

EVERYONE DESERVES a good death—a choice about how they spend their final days, a peaceful, pain-free exit. That is the mission of hospice care. But as corporate profiteers take over end-of-life care in the U.S., the system is failing many people in their moment of greatest need. Policymakers must better regulate this vital service.

The hospice movement got its start in England in 1967. The brainchild of Cicely Saunders, a physician and social worker, it aimed to ease the suffering of the dying by managing their pain and other symptoms and by affording social support to them and their caregivers. The culture around death has long been one of denial. The medical establishment tended to push aggressive treatment on ailing patients and then abandon them once they were deemed incurable. With its emphasis on accepting death and offering compassionate, holistic care to patients and their families, hospice revolutionized the way in which society tends to the terminally ill. By the 1970s the movement had spread to the U.S. Volunteer-led and supported by donations, hospices offered their services free of charge, mostly in the comfort of people's homes. Of the roughly three million Americans who die every year, around half now do so in hospice care.

The trouble began in the 1980s, when Medicare began paying certain hospice providers for care given to people with six months or less to live. Medicare pays a fixed amount to providers for each day that someone is enrolled in hospice, regardless of how much care they actually receive. With this turn of events, for-profit hospices began springing up to take advantage of the government contracts. Today nearly three quarters of hospice agencies operate on a for-profit basis. The sector has become so lucrative that in recent years private equity firms and publicly traded corporations have been snapping up previously nonprofit hospices at record rates.

This takeover of what was once an almost exclusively nonprofit service by for-profit firms has had pernicious effects on hospice care in the U.S. When patients enter into hospice care covered by Medicare, they agree to forego further attempts to cure their terminal illness. In exchange, they are supposed to receive comprehensive comfort care from a team of doctors, nurses, social workers, spiritual advisers and trained volunteers who work together to provide patients and their loved ones with the medical, emotional and social support they need. Although hospice generally does not offer live-in care, agencies promise regular visits from members of the hospice team and 24/7 access to on-call doctors and nurses.

For-profit hospices do a significantly worse job of providing this care than nonprofit agencies do, according to a study by the RAND Corporation. Looking at quality measures such as management of pain and other symptoms, communication with the hospice team, and timeliness of care, the researchers found that nonprofits outperformed for-profits in every category.

In addition, it's easy for profit-seeking providers to use loopholes in the payment

The takeover of what was once an almost exclusively nonprofit service by for-profit firms has had pernicious effects on hospice care in the U.S.

Illustration by Thomas Fuchs

model to game the system—and worse. An investigation by ProPublica, co-published with the *New Yorker* in 2022, detailed example after harrowing example of hospice wrongdoing: agencies had bribed doctors to bring them new patients, enrolled patients without their knowledge and ditched patients when they approached the Medicare reimbursement limit.

Every so often perpetrators of hospice fraud get their comeuppance, as in the case of the owner, CEO, operations manager and medical director at the Merida Group, which runs a network of hospices across Texas. All four were found guilty of roles in a scheme to make false and fraudulent claims to Medicare totaling more than $150 million. Between 2020 and 2023 they were sentenced to more than 41 years in prison combined. But overall, there has been so little oversight of the hospice sector that the rot has spread largely unchecked.

Perhaps it should not come as a surprise, then, that according to a recent survey, the U.S. is a pretty lousy place to die. In an analysis of how well countries around the world deliver end-of-life care, the U.S. was ranked 43rd out of the 81 countries assessed, despite being one of the wealthiest nations. The U.K., whose hospices are generally not-for-profit, took first place.

We must fix hospice. It's an unquestionably daunting task, but last April, after reviewing the effects of private equity on the system, the nonprofit Center for Economic and Policy Research proposed a three-pronged approach that serves as a road map to reform. It advocates for strengthening and enforcing existing policies, such as screening hospice providers carefully for eligibility to receive government payments. It also recommends updating policies to account for the involvement of private equity firms in hospice by, for instance, better preventing anticompetitive mergers and acquisitions. And it argues for developing new policies to close loopholes that can be exploited by corrupt agencies, including moving away from the flat-fee payment model toward one based on patients' individual needs.

Death is big business. We can't let corporate greed dictate our endgame. ⬢

Theoretical AI Harms Are a Distraction

Fearmongering about artificial intelligence's potential to end humanity shrouds the real harm it already causes

BY ALEX HANNA AND EMILY M. BENDER

WRONGFUL ARRESTS, an expanding surveillance dragnet, defamation and deepfake pornography are all existing dangers of the so-called artificial-intelligence tools currently on the market. These issues, and not the imagined potential to wipe out humanity, are the real threat of artificial intelligence.

End-of-days hype surrounds many AI firms, but their technology already enables myriad harms, including routine discrimination in housing, criminal justice and health care, as well as the spread of hate speech and misinformation in non-English languages. Algorithmic management programs subject workers to run-of-the-mill wage theft, and these programs are becoming more prevalent.

Nevertheless, last year the nonprofit Center for AI Safety released a statement—co-signed by hundreds of industry leaders—warning of "the risk of extinction from AI," which it asserted was akin to the threats of nuclear war and pandemics. Sam Altman, embattled CEO of Open AI, the company behind the popular language-learning model ChatGPT, had previously alluded to such a risk in a congressional hearing, suggesting that generative AI tools could go "quite wrong." Last summer executives from AI companies met with President Joe Biden and made several toothless voluntary commitments to curtail "the most significant sources of AI risks," hinting at theoretical apocalyptic threats instead of emphasizing real ones. Corporate AI labs justify this kind of posturing with pseudoscientific research reports that misdirect regulatory attention to imaginary scenarios and use fearmongering terminology such as "existential risk."

The broader public and regulatory agencies must not fall for this maneuver. Rather we should look to scholars and activists who practice peer review and have pushed back on AI hype in an attempt to understand its detrimental effects here and now.

Because the term "AI" is ambiguous, having clear discussions about it is difficult. In one sense, it is the name of a subfield of computer science. In another it can refer to the computing techniques developed in that subfield, most of which are now focused on pattern matching based on large data sets and the generation of new media based on those patterns. And in marketing copy and start-up pitch decks, the term "AI" serves as magic fairy dust that will supercharge your business.

Since OpenAI's release of ChatGPT in late 2022 (and Microsoft's incorporation of the tool into its Bing search engine), text-synthesis machines have emerged as the most prominent AI systems. Large language models such as ChatGPT extrude remarkably fluent and coherent-seeming text but have no understanding of what the text means, let alone the ability to reason. (To suggest otherwise is to impute comprehension where there is none, something done purely on faith by AI boosters.) These systems are the equivalent of enormous Magic 8 Balls that we can play with by framing the prompts we send them as

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questions and interpreting their output as answers.

Unfortunately, that output can seem so plausible that without a clear indication of its synthetic origins, it becomes a noxious and insidious pollutant of our information ecosystem. Not only do we risk mistaking synthetic text for reliable information, but that noninformation reflects and amplifies the biases encoded in AI training data—in the case of large language models, every kind of bigotry found on the Internet. Moreover, the synthetic text sounds authoritative despite its lack of citation of real sources. The longer this synthetic text spill continues, the worse off we are because it gets harder to find trustworthy sources and harder to trust them when we do.

The people selling this technology propose that text-synthesis machines could fix various holes in our social fabric: the shortage of teachers in K–12 education, the inaccessibility of health care for low-income people and the dearth of legal aid for people who cannot afford lawyers, to name just a few.

But deployment of this technology actually hurts workers. For one thing, the systems rely on enormous amounts of training data that are stolen without compensation from the artists and authors who created them. In addition, the task of labeling data to create "guardrails" intended to prevent an AI system's most toxic output from being released is repetitive and often traumatic labor carried out by gig workers and contractors, people locked in a global race to the bottom in terms of their pay and working conditions. What is more, employers are looking to cut costs by leveraging automation, laying off people from previously stable jobs and then hiring them back as lower-paid workers to correct the output of the automated systems. This scenario motivated the recent actors' and writers' strikes in Hollywood, where grotesquely overpaid moguls have schemed to buy eternal rights to use AI replacements of actors for the price of a day's work and, on a gig basis, hire writers piecemeal to revise the incoherent scripts churned out by AI.

Large language models are the equivalent of enormous Magic 8 balls that we can play with by framing the prompts we send them as questions.

AI-related policy must be science-driven and built on relevant research, but too many AI publications come from corporate labs or from academic groups that receive disproportionate industry funding. Many of these publications are based on junk science—it is nonreproducible, hides behind trade secrecy, is full of hype, and uses evaluation methods that do not measure what they purport to measure.

Recent examples include a 155-page preprint paper entitled "Sparks of Artificial General Intelligence: Early Experiments with GPT-4" from Microsoft Research, which claims to find "intelligence" in the output of GPT-4, one of OpenAI's text-synthesis machines. Then there are OpenAI's own technical reports on GPT-4, which claim, among other things, that OpenAI systems have the ability to solve new problems that are not found in their training data. No one can test these claims because OpenAI refuses to provide access to, or even a description of, those data. Meanwhile "AI doomers" cite this junk science in their efforts to focus the world's attention on the fantasy of all-powerful machines possibly going rogue and destroying humanity.

We urge policymakers to draw on solid scholarship that investigates the harms and risks of AI, as well as the harms caused by delegating authority to automated systems, which include the disempowerment of the poor and the intensification of policing against Black and Indigenous families. Solid research in this domain—including social science and theory building—and solid policy based on that research will keep the focus on not using this technology to hurt people. ●

Illustration by Hannah Perry

Accepting Discomfort Could Help You Thrive

Equanimity, a key ingredient of mindfulness meditation, helps people face life's ups and downs

BY J. DAVID CRESWELL

CAN YOU IMAGINE getting a root canal or other major dental procedure without novocaine? A scientist colleague of mine recently told me about a painful exposed nerve in his tooth. Rather than requesting a numbing option from his dentist, he used a "focus in" meditation technique to direct all his attention to his mouth with as much calming equanimity as he could muster. Doing so transformed the pain for a few minutes. Each time the dentist touched the tooth, my colleague felt bubbles of joy, and this feeling lasted until the dentist interrupted by asking, "Why are you smiling?"

A fair question is why anyone would want to be fully aware of intensely negative or painful experiences. But what might sound like a punishing choice—to embrace suffering or distress—may in some instances be helpful. A stream of scientific articles suggests that there are benefits in turning toward discomfort or upsetting emotions with acceptance. In addition, all of us can gain from finding ways to cope with stress and unhappiness—particularly when the circumstances are beyond our control. As a researcher who has studied meditation for more than 20 years, I believe that the cultivation of equanimity, a central element of certain mindfulness-meditation practices, can help.

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It's important to first define the idea of turning toward discomfort. I'm not advocating for people to put themselves in dangerous or excruciating positions. But when we push ourselves into challenging or discomfiting situations, much like trainers who push athletes just past their comfort zone to make gains, learning often happens. Indeed, a 2022 study involving more than 2,000 people demonstrated that the participants who were explicitly encouraged to push themselves into awkward, uncomfortable situations across multiple domains—including taking improv classes to boost self-confidence and reading about opposing political viewpoints—later reported the greatest degree of personal growth.

Another study, published in 2023, found that people who can face negative emotions such as sadness and anger in a neutral way are more satisfied, are less anxious and have fewer symptoms of depression than those who judge their negative feelings harshly. That study aligns with a growing consensus in psychology that suggests we can learn powerful lessons about ourselves if we can sit with our emotions and thoughts with an open, curious mind.

My own research indicates that meditation provides an ideal way to practice turning toward discomfort—particularly when it improves one's equanimity. Broadly, mindfulness meditation is a form of mental training that helps people focus on attending to the present moment in an open and receptive way. "Equanimity" refers to a mental attitude of being at peace with the push and pull of experience. In my laboratory at Carnegie Mellon University, we conducted several clinical trials on developing equanimity during mindfulness-meditation training. This approach includes guided meditation exercises such as using a matter-of-fact voice to label uncomfortable sensations in the body and welcoming uncomfortable feelings by saying "yes" aloud each time a sensation is detected.

To gauge the effectiveness of such interventions, we recruited 153 stressed adults in Pittsburgh and offered them a mindfulness-meditation training program with or without training in equanimity. For example, the mindfulness-only group built skills to recognize ongoing experiences, whereas the equanimity group practiced acceptance of those experiences in addition to the basic recognition. Our equanimity training group had much better outcomes on several measures. After just 14 days of training, the participants who learned equanimity skills had significantly lower biological stress responses when asked to deliver a difficult speech and solve math problems in front of experts in white lab coats. The equanimity skills group also had lower blood pressure and hormonal stress levels.

Illustration by Scott Brundage

In the days after training, people introduced to equanimity exercises reported significantly higher positive emotions and well-being throughout the day and more meaningful social interactions than participants who received mindfulness training without the equanimity component. It was as though developing an attitude of equanimity had transformed their emotional reactivity to stress, helping them better appreciate and savor daily life's many little positive experiences and making them more curious and open to connecting with others.

We are expanding on this work in several ways, including by developing an app that offers equanimity training on demand. We are also conducting trials with participants who have stress-related gastrointestinal disorders. Meanwhile other scientists are further exploring equanimity's power.

In 2022, for instance, researchers based in Australia published a study examining isolation and psychological distress in 578 people during the COVID pandemic. They found that the degree to which people felt alone during that period predicted their depression, anxiety and stress—but this dynamic could be mediated by equanimity. That is, people who reported higher levels of equanimity (based on how much they agreed or disagreed with statements such as "I experience a sense of mental balance regardless of what is happening in my life") reported less psychological distress even though they were feeling isolated. In other words, equanimity can be protective in a way that prevents feelings of social disconnection from leading to mental distress.

Equanimity can help us weather the inevitable periods of suffering that we all face at some point in our life. Many people are hurting and looking for ways to cope. Our social lives are suffering, too, which prompted the U.S. surgeon general to declare a national advisory last year about our surging epidemic of loneliness.

Without question, there are many important steps we need to take collectively to respond to these challenges—including looking closely at societal structures and choices that contribute to these problems. But we can each build resilience on a personal level by cultivating greater acceptance of our experience—good or bad, painful or pleasant—in the present moment. ⬢

How Hot Is "Pepper X"?

The creator reveals his experience tasting the hottest pepper in the world

BY STEPHANIE PAPPAS

A NEW WORLD-RECORD HOLDER has entered the field of hot peppers: Pepper X. This proprietary pepper, bred by Ed Currie, was recognized in October 2023 by Guinness World Records as the hottest pepper ever independently tested. Currie is one of the few people to have tried Pepper X raw. By all reports, the taste test involves a burning sensation followed by several hours of intestinal cramping.

With a spiciness level of 2.693 million Scoville heat units (SHU) on average, Pepper X handily unseated the previous hottest pepper on Earth, the Carolina Reaper—also bred by Currie, who founded the PuckerButt Pepper Company, a hot pepper farm and pepper-product supplier in Fort Mill, S.C. (For comparison, jalapeños reach 2,000 to 8,000 SHU.) SCIENTIFIC AMERICAN caught up with Currie to talk about his heat-seeking trajectory and whether hot peppers can get even spicier.

An edited transcript of the interview follows.

Stephanie Pappas is a freelance science journalist based in Denver.

What is it like in the world of hot pepper breeding? Is it a competitive field?

In the pepper-breeding world, there are really only a few of us who intentionally breed peppers. The rest of the people are growers, and they get what's called an odd phenotype and think they've got a new pepper. It's not that competitive. If it were, the Carolina Reaper wouldn't have held a record for 10 years. That's more just stuff on the Internet. Most of the people who actually breed peppers aren't on social media. We talk via the phone.

What does the day-to-day life of a pepper breeder look like?

Half the year we're processing peppers by drying them or turning them into pepper paste. The other half of the year we're breeding peppers. We cross-pollinate plants that have the attributes we want. If the resulting fruit has what we're looking for, we take the seeds out and plant them. If that comes out the same, that's the first generation. It takes anywhere between eight and 12 generations to stabilize a plant so you can start doing the testing.

At PuckerButt, we don't just breed peppers. We're one of the largest hot pepper farms in the U.S. We make hot sauce and pepper mash and dried pepper and pepper powder for all sorts of different manufacturers. Right now I'm making test batches of hot sauce, doing interviews and drying peppers at the same time.

When you're breeding peppers, what other attributes might you look for besides heat?

Ninety-nine percent of what we do is for flavor and looks. I like getting peppers to look really weird or breeding out different colors.

What's your favorite weird pepper that you've bred?

We have a particular variety of chocolate scotch bonnet that we call a UFO bonnet because it kind of looks like UFOs in pictures. It is a delicious pepper. It's not very high on the Scoville scale, but it is my absolute favorite pepper to eat. Don't get me wrong—I eat the superhot ones on a daily basis, but my favorites aren't superhot. They're in the midrange of the pepper world. [*Editor's Note: The Scoville scale measures the number of times an extraction of a pepper's capsaicinoids needs to be diluted with a mix of sugar and water before a professional panel of tasters can no longer detect those hot compounds. In laboratory tests, a machine called a high-performance liquid chromatograph can* *quantify capsaicinoids and other compounds in dried samples of peppers.*]

What makes Pepper X so hot?
The compound that makes peppers hot is called capsaicin. There are many different capsaicinoids, and these compounds react with a nerve receptor that only mammals have that sends a signal to our brain saying, "This is hot." There are a lot of other compounds that can enhance the heat or tame the heat. You can increase the tannin levels in a pepper that is not so hot, such as a scotch bonnet, and it gives you the perception of more heat.

For Pepper X, I took a pepper that had a different set of capsaicinoids and bred it with the Reaper, and it turned out really hot. Nine out of 10 crossbreeds that we do go nowhere, and we have no expectation when we start. It's just playing around and having fun with science.

What is eating Pepper X like?
In hot sauce and in salsa and candy and things, it tastes delicious. But [when it is eaten] raw, the flavor lasts only for a millisecond, and then the heat is just taking off. And it's not a very pleasant experience. I wouldn't recommend eating it raw to anybody, and if somebody wants me to do it again, they're going to have to pay me a lot of money. A Reaper usually takes me about half an hour to recover from, including the cramps. Pepper X took me five to six hours. But I ate more peppers for dinner that night.

What's the advantage of having a superhot pepper?
The advantage of the superhot peppers is economy of scale. Say you're using cayenne to get a pepper sauce as hot as you want it. You might use two to three pounds of cayenne, whereas with Pepper X, to get the same heat, you would need maybe just an eighth of a gram of dried pepper.

I'll give you an example. There was a manufacturer who was using 11 55-gallon drums of a pepper in a recipe. I knew one of the executives there, and I said, "Just try it with one 15-gallon drum of Reaper." They got the same heat and saved 80 percent of the money they were spending.

Do you think you can go hotter?
Oh, yeah, I know we can. We've tested a lot of peppers at a higher level, but we don't yet have a lot of years of averages. You show the average of the tests [when you're reporting the Scoville rating]; you don't show your single highest test. I think we can achieve a lot more, but there's really not much use for it—unless it tastes good. ●

Fixing Fluttering Hearts

Atrial fibrillation—which can lead to stroke—is on the rise, but new tech can spot it BY LYDIA DENWORTH

TWO YEARS AGO I was walking in a park with an older relative when she suddenly stopped and put her hands out for support. Her heartbeat had gone haywire, causing chest pains and making her feel lightheaded and short of breath. The incident ended after a few minutes, but it was alarming to both of us. Yet it was also familiar for her—she had felt these sensations a few times before. Over the next year these episodes happened more and more often, and eventually she felt unwell most of the time. It was atrial fibrillation, or A-fib, which turns a normal, regular heartbeat into a rapid, irregular and dangerous stutter.

Fortunately, my relative's A-fib has been successfully treated with medication and cardioversion, a procedure that uses a jolt of electricity to shock the heart back into a normal rhythm. But since my introduction to A-fib that day in the park, I've met it repeatedly. Another relative recently needed cardioversion twice. And I learned that a friend had a stroke triggered by A-fib when he was in his 50s. In addition to strokes, A-fib can bring on heart attacks, cardiac failure, blood clots and even dementia.

I'm not imagining the sudden ubiquity of this condition. Its prevalence has quadrupled over the past 50 years, according to recent studies. These high numbers are partly attributable to increased surveillance—the more you look for A-fib, the more you find it. But the jump also reflects the fact that people live longer than they did decades ago, and age is a risk factor.

Illustration by Shideh Ghandeharizadeh

There has been a parallel rise in conditions such as obesity, diabetes and high blood pressure, which also heighten risk, even in younger people. Smoking and sleep apnea are additional risk factors. Epidemiologists now put the lifetime risk of A-fib at about one in three for white people older than 40. For Black people, it is one in five. The reason for that lower prevalence is unclear. It might be partly a result of underdiagnosis.

Yet a third of people who have A-fib don't know it. An episode can come and go quickly (paroxysmal A-fib), so people might feel tired or short of breath for a moment but recover and not go to a doctor about it. A 2023 study estimated that over a two-year period almost one quarter of cases will go undiagnosed.

A-fib occurs when electrical signals in the upper chambers of the heart—the atria—misfire. The resulting irregular heartbeat causes blood to pool instead of being pumped out to the lower chambers. In addition to its deadly consequences, A-fib can make people physically uncomfortable and limit their activities. "We've begun to appreciate the toll A-fib takes on the quality of life," says cardiologist and electrophysiologist Mintu Turakhia of Stanford University.

Atrial fibrillation is also a primary example of the effects of health inequities, says cardiologist Jared Magnani of the University of Pittsburgh: "It's a disease that requires monitoring and detection. And then it requires access to medical care, with a partner in making decisions about things like [medication], and finally more advanced therapies and treatment." A 2022 study published in *Circulation* showed that compared with residents in well-to-do neighborhoods in Ontario, Canada, residents of the province's most deprived areas were less likely to visit a cardiologist or to receive treatment for A-fib and had poorer outcomes.

There has also been a sex gap in diagnosis and treatment, says Louise Segan, a cardiologist and electrophysiologist at the Alfred Hospital and a researcher at the Baker Heart and Diabetes Institute, both in Melbourne, Australia. Segan has treated many women who had previously been told that their A-fib symptoms were caused by anxiety. Some weren't referred for treatment at the same rate as men, she says. Earlier studies suggested women experience more complications after cardiac interventions, but recent research is helping to debunk this idea. An extensive 2023 subanalysis of a large study published in *JAMA Cardiology* showed no significant differences in outcomes by sex for people treated with a new technology called pulsed field ablation.

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

The benefits of detecting A-fib early are considerable. When clinicians can restore normal rhythm, Turakhia says, it alters the trajectory of disease and outcomes for years to come. Paroxysmal A-fib is easier to treat than the more serious "persistent" version of the disease. For all types, lifestyle changes such as improving nutrition, stopping smoking and cutting back on alcohol are more effective early as well. There are also medications that can slow heart rate and control the rhythm. In November 2023 leading medical groups issued new guidelines for preventing and treating A-fib. They call for a stronger focus on heart-healthy habits and early, more aggressive efforts to control heart rhythms.

The good news is that A-fib is getting more attention, in part thanks to publicity campaigns—one features basketball great and writer Kareem Abdul-Jabbar talking about his diagnosis with the condition. A-fib is also well suited to the growing popularity of wearable technology, which could catch more undiagnosed cases. For instance, the 2019 Apple Heart Study showed that the Apple Watch could successfully detect irregular heart rhythms. Confirmation of A-fib still requires further testing, but that, too, can be done at home with wearable electrocardiography patches, which record days' worth of data and get returned to physicians for analysis. This type of ongoing monitoring is particularly useful for a condition that can come and go before a patient gets to a doctor's office.

More than 400,000 people downloaded the Apple Study app and agreed to participate in the research, which suggests A-fib is on people's minds. And the earlier it's on their minds, the less likely it is to be in their hearts. ⬣

Illustration by Jay Bendt

The Crab Nebula, as seen in infrared light by the James Webb Space Telescope

New View of the Crab Nebula

The James Webb Space Telescope may shed light on the supernova remnant's origins BY PHIL PLAIT

A LITTLE MORE THAN 969 years ago—on July 4, 1054, to be precise—light reached Earth from one of the universe's most energetic and violent events: a supernova, or an exploding star.

Although its source was 6,500 light-years from us, the supernova's light was so bright that it could be seen during the daytime for weeks. Various civilizations around the world documented its appearance in records from that time, which is how we know the very day it began. Hundreds of years later astronomers observing the sky near the constellation Taurus noted what looked like a cloud of mist near the tip of one of the bull's horns. In the mid-19th century astronomer William Parsons made a drawing of this fuzz ball based on his own observations through his 91-centimeter telescope, noting that it looked something like a crab (maybe if you squint). And the name stuck: we still call it the Crab Nebula today (*nebula* is Latin for "fog").

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

We now know that the Crab is a colossal cloud of debris that got blasted away from the explosion site of that ancient supernova at five million kilometers per hour. In the past millennium that material has expanded to a size of more than 10 light-years across, and it is still so bright that it can be seen with just binoculars from a dark site. It's a favorite among amateur astronomers; I've seen it myself from my backyard.

Through bigger hardware, of course, the view is way better. Astronomers recently aimed the mighty James Webb Space Telescope (JWST) at the Crab in hopes of better understanding the nebula's structure. What they found might even solve a long-standing mystery about its origins in the death throes of a bygone star.

The image is in some ways familiar. It's quite a bit like the one taken in 2005 by the Hubble Space Telescope. Both photographs reveal an almost football-shaped cloud of smooth, vaporous material wrapped in wispy but well-defined multicolored tendrils. At the cloud's center, nearly shrouded by the debris, is a pinpoint of light: a pulsar, the leftover core of the massive star that exploded so long ago.

Hubble observes mainly in visible light—the same kind that our eyes see—and its image reveals mostly shock waves rippling through the cloud's material and hot gas excited by the central pulsar's powerful radiation. JWST, in contrast, is sensitive to infrared light, so its image shows different structures.

(As an aside, the nebula has expanded noticeably in the nearly two decades since the Hubble shot was taken. The European Space Agency has a tool on its website, esawebb.org, that lets you shift views between the Hubble and JWST images of the nebula, and you can easily see the material moving outward.)

Rather than revealing shock waves and hot gas, the JWST images show features arising from the Crab's dust and its synchrotron radiation. The former is composed of tiny grains of silicates (rocky material) or complex carbon molecules similar to soot, and it appears primarily in the nebula's outer tendrils. The latter is the eerie glow emitted by trapped electrons spiraling at nearly the speed of light around the pulsar's intense magnetic field lines. Synchrotron radiation is usually best seen in radio and infrared imaging, so it dominates the smoother inner cloud in JWST's view.

One of the filters used in these observations is tuned for light from hot iron gas, tracing the ionized metal's distribution throughout the tendrils. These measurements, astronomers hope, might answer a fundamental question about the star that created this huge, messy nebula nearly a millennium ago.

Stars like our sun fuse hydrogen into helium in their core. This thermonuclear reaction creates vast amounts of light and heat, allowing the star to shine. When the sun runs out of hydrogen to fuse, it will start to die, swelling into a red giant before finally fading away. But we have many billions of years before our star's demise is set to begin, so breathe easy.

Stars that are more massive than the sun can fuse heavier elements. Helium can be turned into carbon, and carbon can be

We now know that the Crab is a colossal cloud of debris that got blasted away from the explosion site of an ancient supernova.

turned into magnesium, neon and oxygen, eventually creating elements such as sulfur and silicon. If a star has more than about eight times the mass of our sun, it can squeeze atoms of silicon so hard that they fuse into iron—and that spells disaster. Iron atoms take more energy to fuse than they release, and a star desperately needs the outward push from fusion-powered energy to support its core against the inward pull of its own gravity. The star's core loses that support once iron fusion begins, initiating a catastrophic collapse. A complex series of processes occurs, and in a split second a truly mind-stomping wave of energy is released, making the star explode.

If the core itself has less than about 2.8 times the mass of our sun, it collapses into a superdense, rapidly spinning neutron star. Its whirling magnetic fields sweep up matter and blast it outward in two beams, creating a pulsar. But if the core is more massive than that, its gravity becomes so strong that it falls in on itself, becoming a black hole.

The Crab Nebula has a pulsar, indicating that the core of its supernova progenitor was less than 2.8 times the mass of the sun. But the star itself may have been anywhere from eight to 20 times the sun's mass in total. Right away this presents a problem. The mass of the Crab pulsar is less than twice the sun's mass, and the estimated mass of the entire nebula is as much as five times that of the sun. But that adds up to only seven solar masses at most. The star must have been more massive than that to explode, so where did the rest of the material go? It's possible there is hidden mass surrounding the pulsar, embedded in the nebula, as yet undetected by telescopes. The structure of the nebula could provide clues to this material or at least point astronomers toward places to look deeper.

Even the star itself is something of an enigma. How massive was it? Taking the measure of the nebula might offer answers. Iron-core collapse is just one way a massive star can explode. For a star around eight to 12 times the sun's mass, there is another avenue to annihilation. The core of such a star is incredibly hot, and there are countless free electrons swimming in that dense, searing soup. A quantum-mechanical property called degeneracy pressure usually makes the electrons resist compression, adding support to the core. But during one specific stage of stellar fusion, it's possible for those electrons to instead be absorbed into atomic nuclei, removing that pressure. This change can trigger a core collapse before the star has had a chance to create iron.

Scientists first proposed this supernova-triggering electron-capture mechanism in 1980. But it wasn't observed until 2018, via telltale signatures in the light from a distant exploding star in another galaxy. When astrophysicists telescopically squint just so at the Crab Nebula—much like they do to perceive its crustacean shape—they see hints that it might have exploded in a similar fashion. But such squints are a poor substitute for certainty; greater clarity may come from JWST's measurement of how much iron the nebula holds. The element's abundance could allow researchers to distinguish between a "normal" core collapse and one triggered by electron capture. Those data are still being analyzed, but let's hope this puzzle can be solved as well.

That's probably why the recent program to observe the Crab emerged victorious in the stiff competition for JWST's precious observing time; the parsimonious prospect of solving two different mysteries with one set of observations is just the kind of thing scientists love. Of course, any image of the Crab Nebula is guaranteed to be jaw-droppingly beautiful, too. That doesn't hurt, either. ⬢

Environmental Protection Does Not Kill Jobs

The argument that we must choose between saving nature and strengthening the economy is a false dichotomy

BY NAOMI ORESKES

ONE OF THE MOST damaging logical fallacies is the "fallacy of the excluded middle," also known as a false dichotomy or false binary—the ploy of presenting a problem as either/or with no other choices and no middle ground. It's often used to make people reject something they want by persuading them they can't have it unless they give up something else they want even more. An example is the supposed trade-off between jobs and the environment.

Since 1984 the Gallup polling group has been asking the following question: "With which one of these statements about the environment and the economy do you most agree—protection of the environment should be given priority, even at the risk of curbing economic growth (or) economic growth should be given priority, even if the environment suffers to some extent?" Antienvironmental forces exploit this dichotomy. For example, while on the campaign trail during the United Auto Workers strike last fall, Donald Trump said, "You can be loyal to American labor, or you can be loyal to the environmental lunatics, but you can't really be loyal to both. It's one or the other."

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and coauthor of *The Big Myth* (Bloomsbury, 2023).

Most Americans are not lunatics, but they care a lot about the environment, and there is obvious public interest in fresh air, clean water, and beautiful places to walk and rest. So antienvironmental politicians and polluting industries rely on a dichotomous framing to claim that in trashing environmental protection, they are protecting something more valuable: jobs.

In fact, numerous studies show that protecting the environment is not bad for the economy. In the 1980s—soon after landmark federal statutes such as the Clean Air and Clean Water Acts were passed—some studies suggested that the economic slowdown in that decade was caused by environmental legislation.

But better, larger and longer-term studies completed since then have refuted that claim. For example, one study found that productivity at stringently regulated oil refineries in the heavily controlled Los Angeles air basin increased during the study period—1987 to 1992—whereas refinery productivity decreased in other regions. A recent review of the peer-reviewed literature concluded that "environmental regulations have had very little effect on employment in the regulated industry." In other words, environmental protection does not kill jobs.

What is more, many environmentally destructive jobs are notoriously short-lived. Mineral extraction is famously associated with boom-and-bust economics—think "gold rush"—and several studies have shown that the fracking "boom" of the early 2000s has already gone bust. In his 2021 book, *Up to Heaven and Down to Hell: Fracking, Freedom, and Community in an American Town,* Colin Jerolmack reports that the actual number of jobs that were created by the industry was often far less than claimed, and many of them proved ephemeral. The Multi-State Shale Research Collaborative found that "firms with an economic interest in the expansion of drilling" and their allies systematically exaggerated its impact on employment.

For instance, in 2012 the U.S. Chamber of Commerce claimed that fracking in Pennsylvania, Ohio and West Virginia had created more than 300,000 new jobs. But the Pennsylvania Department

Illustration by Izhar Cohen

of Labor and Industry counted only about 18,000 in core industries and about 5,600 in ancillary industries, and according to the nonprofit Ohio River Valley Institute, little of the income they generated stayed in local communities. In contrast, environmental restoration creates jobs in projects that typically employ local laborers, use mostly local materials and, because they support tourism and recreation, often yield durable benefits.

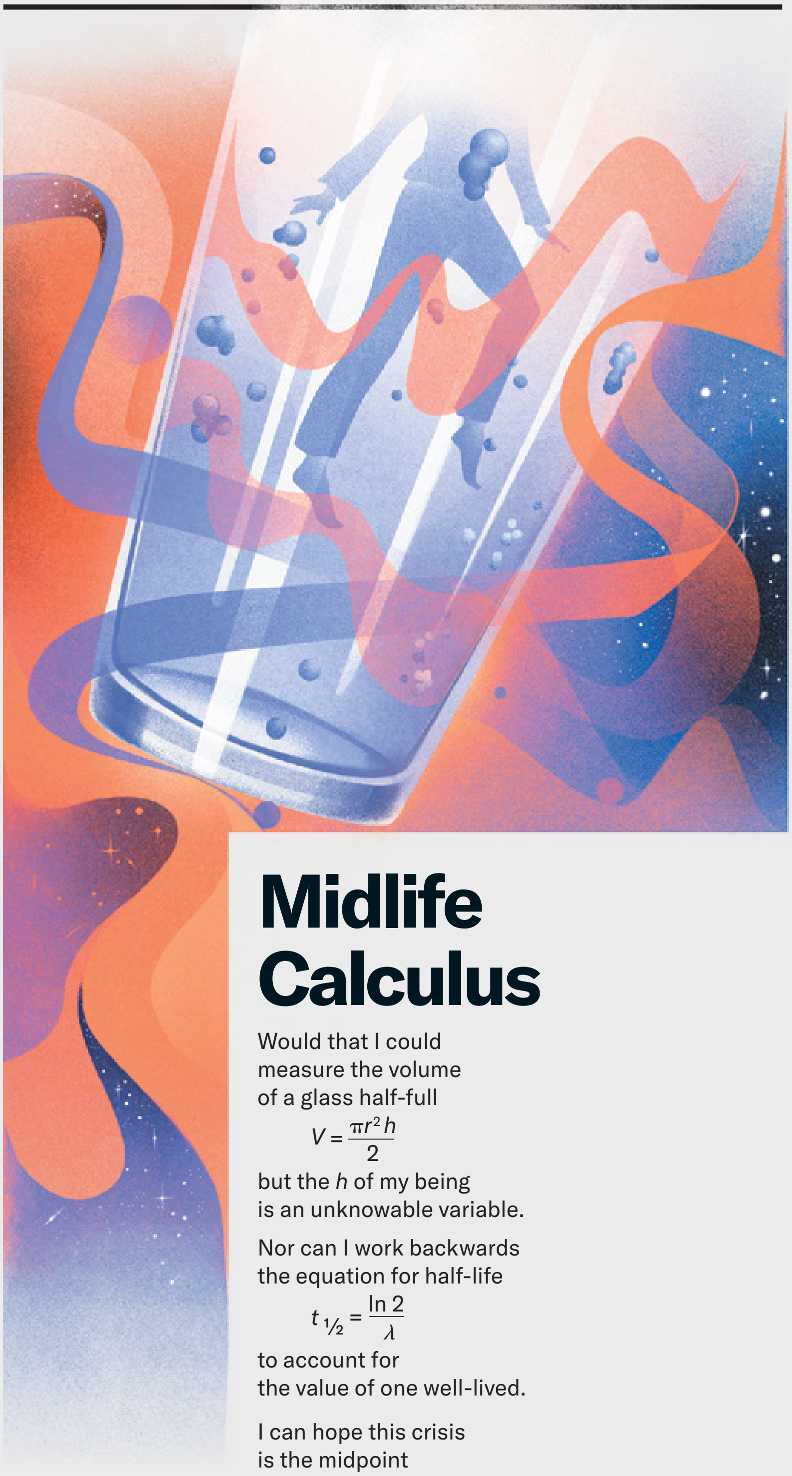
Environmental protection is also good for public health, which in turn is good for the economy, because sick people generally can't work well and sometimes can't work at all. A study published in the journal *Science* last November estimated that nearly half a million deaths in the U.S. could be attributed to fine particulate air pollutants from coal-fired power plants between 1999 and 2020.

It's not just that being exposed to toxic chemicals and polluted air and water is bad—something we've known for centuries—but also that time spent in nature is good. Although the details can be hard to pinpoint, various studies and reviews have documented positive effects of a clean and green environment, particularly on mental health, cognition and blood pressure.

One of the unintended negative consequences of COVID-19 lockdowns for some people might have been the adverse effect of being stuck indoors. A review study published in 2022 found that exposure to nature during the COVID pandemic was associated with lower levels of depression, anxiety and stress and with greater happiness and life satisfaction.

Nature exposure was also "correlated with less physical inactivity and fewer sleep disturbances." During lockdowns, many people spent more time than usual outdoors. Recovery and resilience in future public health crises, the authors of this review concluded, "might be improved with nature-based infrastructure, interventions, designs and governance."

So next time that you hear someone assert that it's either the economy or the environment, don't believe it. And let's hope that the good folks at Gallup will realize that it's time to ditch this damaging false dichotomy.



Midlife Calculus

Would that I could
measure the volume
of a glass half-full

$$V = \frac{\pi r^2 h}{2}$$

but the h of my being
is an unknowable variable.

Nor can I work backwards
the equation for half-life

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

to account for
the value of one well-lived.

I can hope this crisis
is the midpoint

$$\left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2}\right)$$

and that I don't outlive
the remembrance of my past
to be caught in a Möbius present.

I have learned enough, now,
to measure precisely how much it holds,
the irregular curves—
less the difference of the holes life left—
and yet, my heart is still full.

Britt Kaufmann is a poet and math tutor who lives in Burnsville, N.C. She took her first calculus course at age 47. Her first full-length collection of poetry, also called *Midlife Calculus,* will be published by Press 53 in the fall of 2024.

Illustration by Masha Foya

A Dinosaur Can Teach Us How to Do Better Science

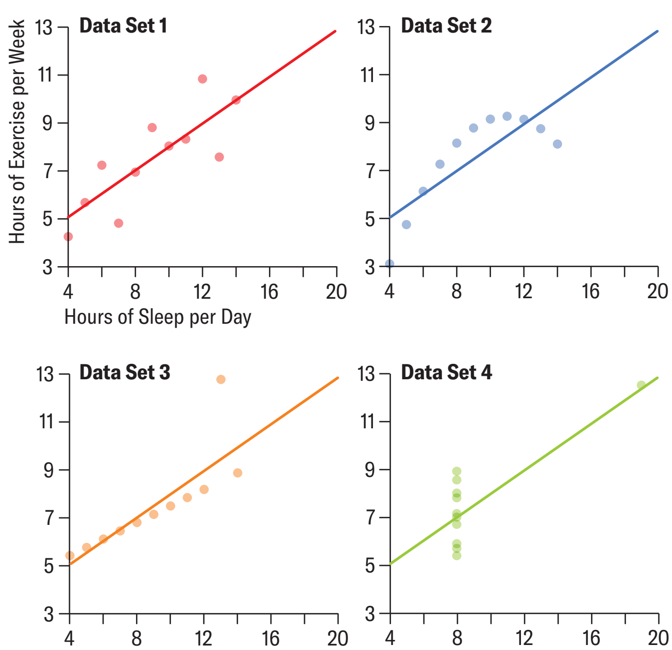
"Anscombe's quartet" and the "datasaurus dozen" demonstrate the importance of visualizing data

BY JACK MURTAGH

MARK TWAIN ONCE WROTE, "There are three kinds of lies: lies, damned lies, and statistics." (He attributed the quip to former British prime minister Benjamin Disraeli, but its true origin is unknown.) Given the foundational importance of statistics in modern science, this quote paints a bleak picture of scientific endeavors. Several generations' worth of scientific progress have proved Twain's sentiment to be an exaggeration. Still, we shouldn't discard the wisdom in those words. Although statistics is an essential tool for understanding the world, employing it responsibly and avoiding its pitfalls require a delicate dance.

One maxim that should be etched into the walls of all scientific institutions is to visualize your data. Statistics specializes in using objective, quantitative measures to understand data, but there is no substitute for graphing something out and getting a look at its shape and structure with one's own eyeballs. In 1973 statistician Francis Anscombe feared that others in his field were losing sight of the value of visualization. "Few of us escape being indoctrinated" with the notion that "numerical calculations are exact, but graphs are rough," he wrote. To quash this myth, Anscombe devised an ingenious demonstration known as Anscombe's quartet.

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



Statistician Francis Anscombe showed that very different data sets can have the same statistics. These four graphs all have the following summary statistics:

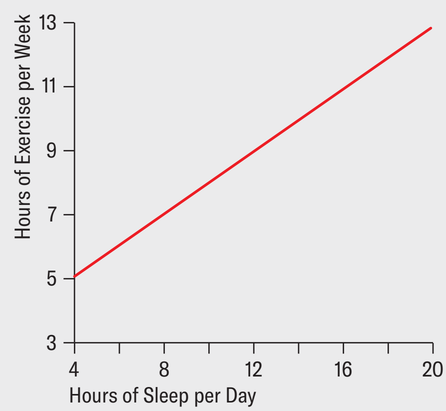
Mean, *x*-axis = 9
Mean, *y*-axis = 7.5
Standard deviation, *x*-axis = 3.32
Standard deviation, *y*-axis = 2.03
Correlation = 0.816

Together with its wacky successor, the datasaurus dozen, nothing more dramatically communicates the primacy of visualization in data analysis.

To appreciate Anscombe's quartet, let's slip into the lab coat of a scientist. Suppose you're interested in the relation between how much people exercise and how much they sleep. You survey a random sample of the population about these habits, record the answers in a spreadsheet and run the results through your favorite statistics software. The summary statistics look like the following (this example is not based on real data):

Hours of exercise per week: average, 7.5;
standard deviation, 2.03
Hours of sleep per day: average, 9;
standard deviation, 3.32
Correlation between the two: 0.816

On average, the people in your sample exercise 7.5 hours per week and sleep nine hours per day. Standard deviation measures how much variation there is in your sample. Here it's moderate for both variables, indicating that most people you surveyed don't veer too much from the averages. The two are highly correlated, which implies that people who exercise more are also likely to sleep more. The software also outputs a line of best fit, which describes the general trend of your data, as shown below.



Given this summary, it might be tempting to suppose that the data look something like data set 1 in the plots to the left on this page. Each dot represents one person in your survey and is positioned according to that person's individual sleep and exercise habits. The chart depicts a strong upward linear trend, which suggests that as people

Sources: R: A Language and Environment for Statistical Computing. R Core Team. R Foundation for Statistical Computing, 2021; "Graphs in Statistical Analysis," by F. J. Anscombe, in *American Statistician*, Vol. 27, No. 1; February 1973 (*sleep and exercise graphs*); Jumping Rivers; "Same Stats, Different Graphs: Generating Datasets with Varied Appearance and Identical Statistics through Simulated Annealing," by Justin Matejka and George Fitzmaurice, in *CHI '17: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*; May 2017 (*datasaurus dozen graphs*)

Graphics by Amanda Montañez

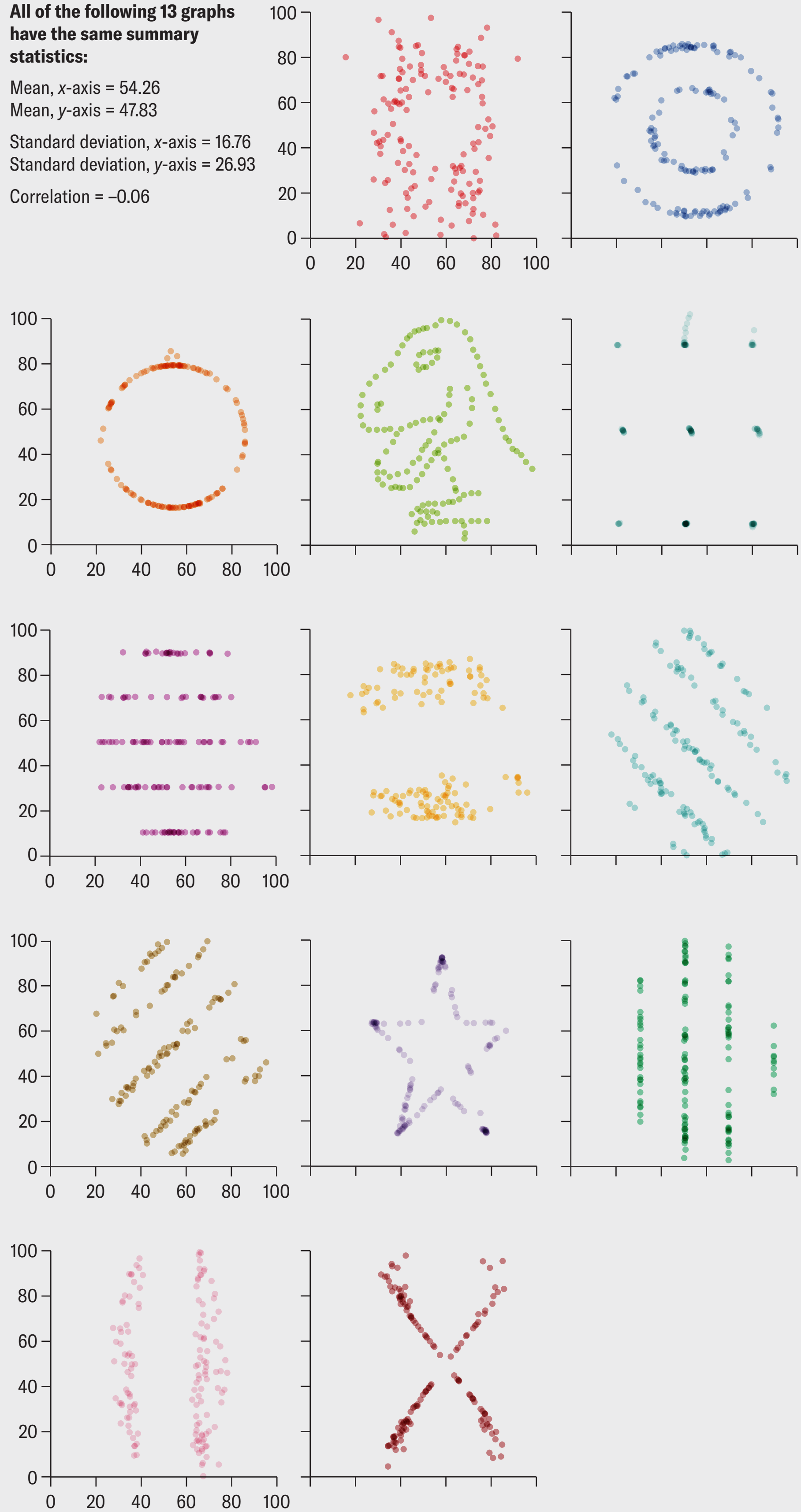
exercise more, they also sleep more (perhaps because both are indicative of a generally healthy lifestyle or because workouts are fatiguing). There is little of the random variation characteristic of the real, messy world. Anscombe showed that, amazingly, all four of the different data sets shown on the opposite page have identical summary statistics.

Data set 2, despite having the same summary statistics as data set 1, tells a completely different story when plotted point by point. The relation among the actual values is clearly not linear, and for whatever reason, exercise starts to taper off for the people who sleep the most. Data set 3 shows a perfect linear relation except for one outlier who exercises an atypical amount and skews the results. In data set 4, almost everybody sleeps exactly eight hours per day, and their sleep habits have no correlation to how much they exercise, whereas one person in the sample sleeps almost 20 hours a day and presumably spends all their waking time exercising. Notice how the same statistics lead us to very different conclusions once we visualize the data.

Despite its popularity, nobody knows how Anscombe concocted his quartet. Justin Matejka and George Fitzmaurice of Autodesk Research in Toronto sought to rectify this gap in knowledge and took the concept to its extreme. They demonstrated a general-purpose method for taking any data set and transforming it into any target shape of your choosing while preserving whichever summary statistics you want (up to two decimal places). The results are the datasaurus dozen.

All the scatterplots on this page have the same summary statistics! Astute readers might notice that it's a datasaurus baker's dozen. The dinosaur data set was the starting point from which all the others were generated. (It's an homage to data-visualization expert Alberto Cairo's tongue-in-cheek *Tyrannosaurus rex* data set.) Clearly, summary statistics alone tell an inadequate part of the story.

Anscombe would probably be proud that his quartet lives on as a common pedagogical demonstration in modern statistics classes. As baseball legend Yogi Berra said, "You can observe a lot by watching." ⬢



All of the following 13 graphs have the same summary statistics:

Mean, *x*-axis = 54.26
Mean, *y*-axis = 47.83

Standard deviation, *x*-axis = 16.76
Standard deviation, *y*-axis = 26.93

Correlation = –0.06

Serious and Silly Science

A collection of 71 micro essays on subjects ranging from hangover myths to pansexual primates BY CHUCK WENDIG

NONFICTION As an author of science-fiction and horror novels, I am called on to seem like an expert on the various topics I write about—Pandemics! Artificial intelligence! Ants!—when really I'm just trying to use true facts to suspend readers' disbelief and convince them that my made-up worlds are rooted in reality. One of the greatest tools in my toolbox, then, is nonfiction that is both salient and accessible, so that I may steal its concepts. I'm always looking for material that is relevant to the work at hand but isn't so demonstrative of its expertise that it sails over my head like a near-miss asteroid. (Or as one essay about catastrophic cosmic collisions in this book calls them: ASSteroids.)

In *How to Win Friends and Influence Fungi,* I have found my new holy bible: a scattershot blast of science-y, math-y, tech-y micro essays that span a dizzying array of subjects. The book serves as an aggregation of some of the most memorable presentations in the 20-year history of Nerd Nite, a monthly event hosted across 100 cities worldwide designed to let audiences show up, have a drink and learn some weird, true stuff. Editors Chris Balakrishnan and Matt Wasowski—Nerd Nite is their brain baby—wanted to make it possible for anyone to flip to a page and partake in a short burst of fascination; with illustrations by Kristen Orr, the book succeeds in making its diverse subject matter immediately accessible. The style is light, quirky, funny and occasionally hilarious. The 71 essays are roughly gathered into chapters, including "Creature Features," "Pathogens and Parasites," "Death and Taxes (But Really, Just Death)," and a sex-themed section, "Doing It."

Want to know why someone's eating noises make you murderous? Jane Gregory, a clinical psychologist, will inform you of a condition she herself suffers: misophonia, or "when small repetitive sounds cause big negative reactions." Curious about how birds have sex? Nerd Nite founder Balakrishnan, who is also a biologist, writes about cloacal kisses and duck penises. Did you know you probably suffer from veisalgia from time to time, even though you don't know what that is? It's a fancy word for hangovers, and neuroscientist Paula Croxson will teach you all you need to know about it and its many—purely theoretical, mostly fake—cures.

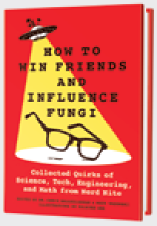
That's only a shaving of the iceberg of information contained in the collection's pages. You'll also find bits on pansexual primates, defecating in space, maggot therapy, arachnid sex catapults, the surprising awesomeness of GMOs, the surprising not so awesomeness of antibacterial soap, and *chindōgu,* the Japanese art of making eccentric, largely "un-useless" inventions.

"Bits" is the key word here—most of these essays are two, three, maybe four pages. None of them would qualify as a full meal's worth of knowledge, and sometimes the essays end abruptly just as they get going, thus delivering a sense of *info-discuss interruptus* that leaves you frustrated and wanting to know more, more, more. But if you approach this book as a grazing table full of scientific *amuse-bouches,* each a single bite of fascination, then your curiosity will be piqued instead of fully satisfied, motivating you to more deeply explore the subjects that especially catch your attention.

As a person who occasionally has the sense of humor of a 12-year-old, I dig the pop culture references and the abundant puns, and count me in for all the lurid, silly jokes about sex stuff and our various bodily excretions, puerile as they sometimes are. That said, it's not all about the chuckles: You'll find sharp, measured takes on disability, sexuality, mental illness, the open Internet, and further, the book does good work in attempting to combat misinformation and disinformation in the spaces of science and technology. For instance, in an essay on the public panic over genetically modified organisms ("They're Putting Acid in Our Food!"), Tracy Kurtz, a Nerd Nite organizer in Fargo, N.D., reminds us that we've been genetically modifying our food for thousands of years.

If the book has one weakness, it's that the essays are inequal in quality. Many are written well, successfully connecting readers to the implications of the science and making jokes that earn their chuckles. But several feel too shallow and don't deliver entirely on either knowledge or laughs.

These ups and downs are perhaps to be expected given the sheer breadth of subject matter and the fact that each micro essay is penned by a different author. Ultimately, the fun here is in the joy of discovery, in coming away effervescent with renewed curiosity for the universe in which we live.



How to Win Friends and Influence Fungi: Collected Quirks of Science, Tech, Engineering, and Math from Nerd Nite edited by Chris Balakrishnan and Matt Wasowski. St. Martin's Press, 2024 ($30)

Chuck Wendig is the *New York Times* best-selling author of *Wanderers, The Book of Accidents,* and more.

Illustration by London Ladd

Nuclear Mysteries

An exploration of the uncertainties inside America's atomic-arsenal update

fotograzia/Getty Images

NONFICTION The central premise of Sarah Scoles's fascinating new book is at once straightforward and disconcerting: the U.S. is in the middle of a massive refurbishment campaign to upgrade its geriatric nuclear arsenal—and yet nobody, not even the people charged with that task, knows precisely how these weapons operate. The inner workings of the most destructive thing human beings have ever built remain, in large part, a mystery.

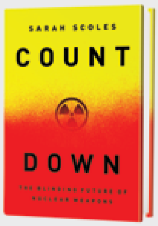
From that starting point, Scoles, who is a contributor to *Scientific American,* ventures on a kaleidoscopic interrogation of the weird, secretive fraternity that is America's nuclear sector. Traditionally, it's not a particularly well-explored space, despite our recent, *Oppenheimer*-fueled obsession with all things atomic. The reality of modern nuclear-weapons work is at once much less spectacular and much more intricate than one might imagine—an entire alphabet of acronymic agencies responsible for everything from cleaning up radioactive spills to conducting CSI-style investigations of hypothetical dirty-bomb detonations.

At its most interesting, *Countdown* is an exploration of uncertainty in a field whose awesome destructive capacity makes uncertainty a deeply worrying thing. Because of bans on aboveground nuclear testing, the traditional method of figuring out how nuclear bombs work—namely, blowing them up—isn't feasible anymore. So scientists are left with computer models and other esoteric techniques to try to figure out, for example, how the radioactive matter in nuclear bombs changes over many decades in storage.

The weakest part of the book is, unfortunately, outside of Scoles's control. Few facets of government work are as heavily classified as the nuclear program, and as a result, many anecdotes and narrative threads come to a hard stop not at any satisfying conclusion but rather when the documentary trail becomes inaccessible or when an interview subject turns reticent.

Nevertheless, Scoles does get at the heart of the many paradoxes that frame the nuclear age. The people she speaks to—some of them inspired to do this work because they believe that nuclear weapons are a means of deterrence, a means of making the world safer—are clearly engaged in their own internal struggles with self-doubt. In this way, a book chronicling the stewards of our deadliest weapons of war becomes, at times, the story of people at quiet war with themselves.

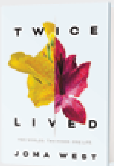
—*Omar El Akkad*



Countdown: The Blinding Future of Nuclear Weapons by Sarah Scoles. Bold Type Books, 2024 ($30)

IN BRIEF

Twice Lived by Joma West. Tordotcom, 2024 ($26.99)

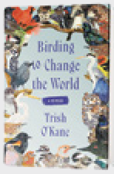


Joma West's urgent, slice-of-life novel imagines a reality where, from the womb and into adolescence, some children "switch" at unpredictable intervals, vanishing into a parallel world, leaving behind their selves, names and families until they switch back. At some point they settle into a single existence. This moving book explores how different upbringings can yield different selves, centering on one teen—Canna in one life and Lily in the other—and her mother in each place, both of whom fear the next switch might mean Canna/Lily never returns. As each iteration of the protagonist strives to stay in the world she loves, West's brisk, chatty scenecraft proves as resonant emotionally as the premise is conceptually. —*Alan Scherstuhl*

A Fire So Wild: A Novel by Sarah Ruiz-Grossman. Harper, 2024 ($25.99)

Sarah Ruiz-Grossman presents a passionate yet critical observation of the devastating effects of a California wildfire that indiscriminately upends the lives of residents from various socioeconomic backgrounds. Wealthy Abigail organizes fundraisers for low-income housing, but now finds her own house reduced to ashes. Sunny, a homeless construction worker, was promised one of the new apartments, but the fire puts that on hold. Middle-income high school teacher Gabriel and his ex-wife search for their teenage daughter, who was with Abigail's son during the blaze. Ruiz-Grossman's piercing commentary reveals the inequality and injustices of climate change for people just trying to live their lives. —*Lorraine Savage*

Birding to Change the World: A Memoir by Trish O'Kane. Ecco, 2024 ($29.99)



Struggling to cope with the aftermath of Hurricane Katrina, Trish O'Kane becomes an "accidental birder" when her connection with a single cardinal opens her eyes to the hope and healing of birdwatching. As a Ph.D. student and passionate amateur ornithologist in Wisconsin, O'Kane attempts to defend the local bird populations against constant threats by emulating the birds themselves: a starling murmuration, a chevron of geese, a squawking flock of mobbing crows represent "avian attributes, talents, and skills our species urgently needs." Fascinating revelations (even about the humble sparrow) punctuate this thoughtful discussion of complex birding issues such as wildlife management and environmental justice. —*Dana Dunham*

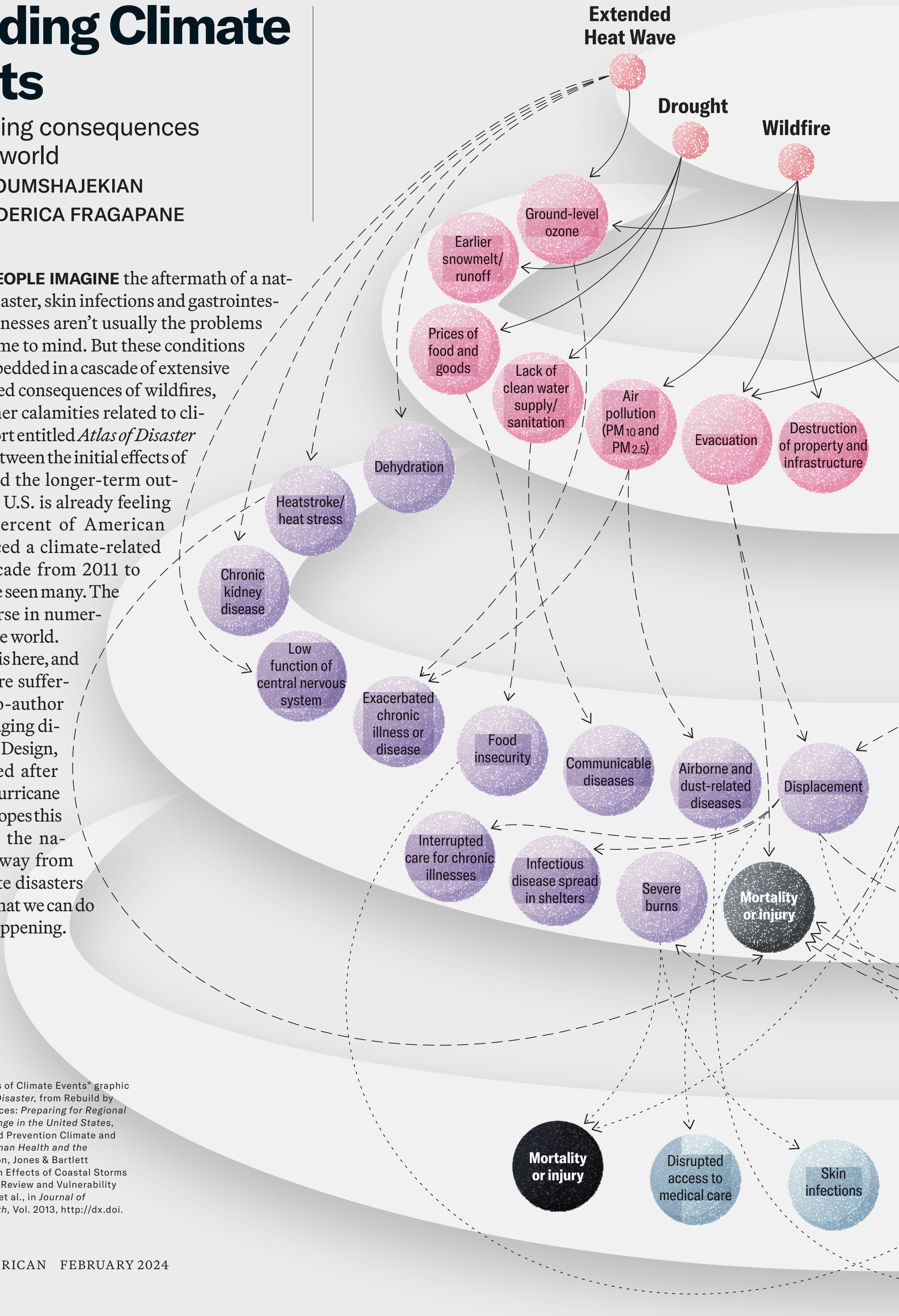
Cascading Climate Impacts

The far-reaching consequences of a warming world

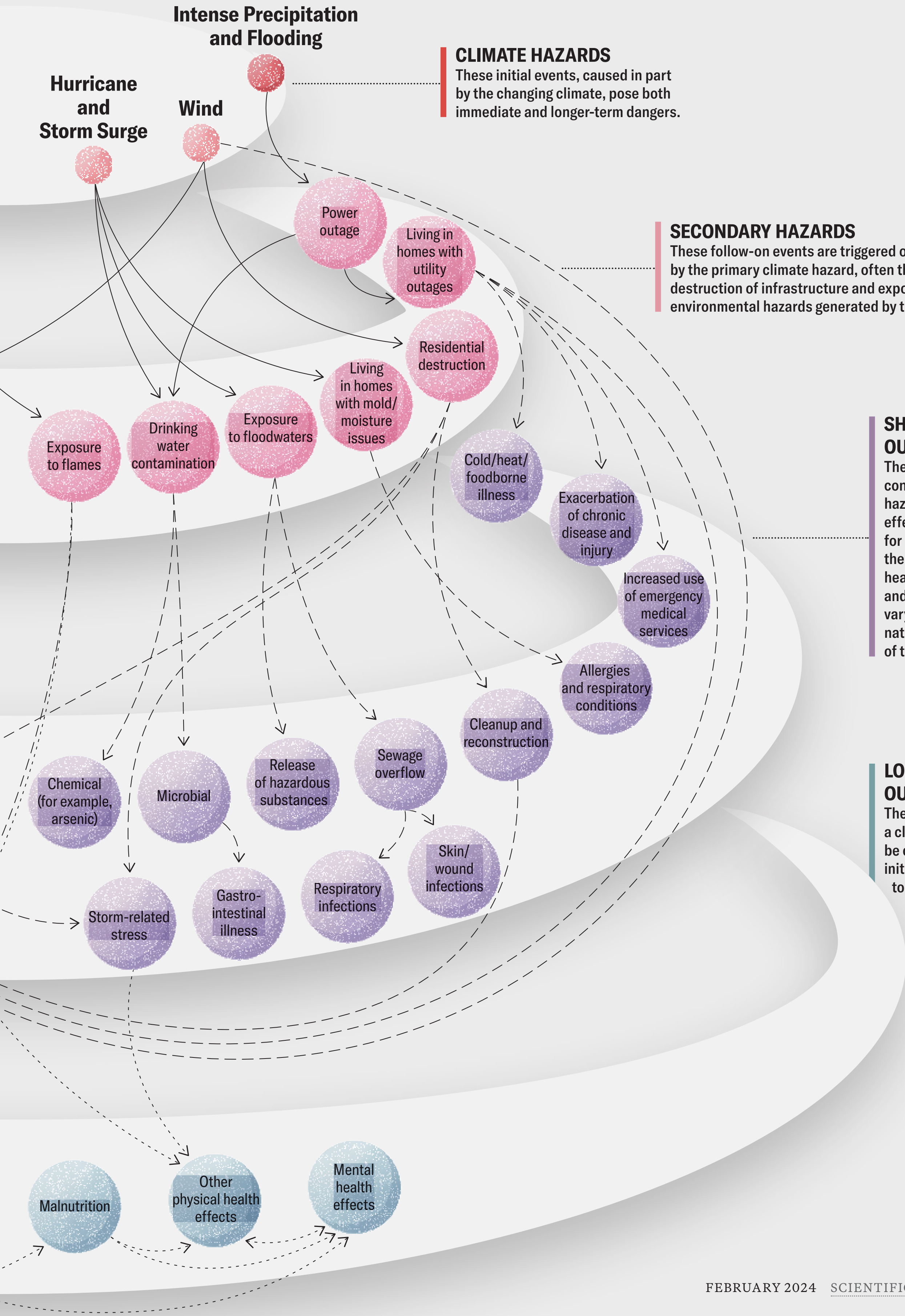
TEXT BY LORI YOUMSHAJEKIAN
GRAPHIC BY FEDERICA FRAGAPANE

WHEN PEOPLE IMAGINE the aftermath of a natural disaster, skin infections and gastrointestinal illnesses aren't usually the problems that come to mind. But these conditions are embedded in a cascade of extensive and often unexpected consequences of wildfires, hurricanes, and other calamities related to climate change. A report entitled *Atlas of Disaster* connects the dots between the initial effects of climate hazards and the longer-term outcomes. Most of the U.S. is already feeling the impact—90 percent of American counties experienced a climate-related disaster in the decade from 2011 to 2021, and some have seen many. The damage is even worse in numerous other parts of the world.

"Climate change is here, and our communities are suffering," says report co-author Amy Chester, managing director of Rebuild by Design, a nonprofit founded after the devastation of Hurricane Sandy in 2012. She hopes this research will shift the national discussion away from what to do if climate disasters occur and toward what we can do now that they are happening.



Inspired by "Cascading Impacts of Climate Events" graphic by Geethanjali MR, in *Atlas of Disaster*, from Rebuild by Design; Rebuild by Design sources: *Preparing for Regional Health Impacts of Climate Change in the United States*, Centers for Disease Control and Prevention Climate and Health Program, July 2020; *Human Health and the Climate Crisis*, by Gail L. Carlson, Jones & Bartlett Learning, January 2022; "Health Effects of Coastal Storms and Flooding in Urban Areas: A Review and Vulnerability Assessment," by Kathryn Lane et al., in *Journal of Environmental and Public Health*, Vol. 2013, http://dx.doi.org/10.1155/2013/913064



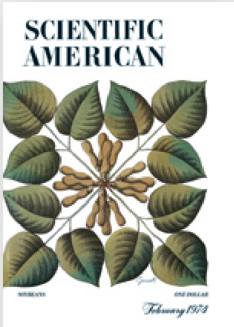
CLIMATE HAZARDS
These initial events, caused in part by the changing climate, pose both immediate and longer-term dangers.

SECONDARY HAZARDS
These follow-on events are triggered or made worse by the primary climate hazard, often through the destruction of infrastructure and exposure to environmental hazards generated by that first event.

SHORT-TERM OUTCOMES
These are the immediate consequences of a climate hazard and secondary effects that may continue for days or weeks after the event. They can involve health, environmental and social effects and vary depending on the nature and severity of the climate hazard.

LONG-TERM OUTCOMES
The lingering effects of a climate hazard might not be obviously linked to the initial event. Often related to complex social issues or wide-ranging health outcomes, these effects can persist for many years after a disaster.

50, 100 & 150 Years



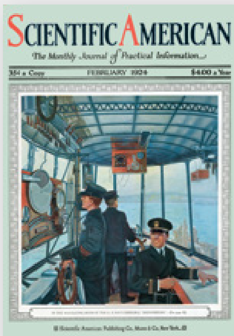
TELESCOPE TO PROBE HUBBLE CONSTANT

1974 “NASA is planning a 120-inch reflecting telescope to be launched in the early 1980s. The Large Space Telescope will probably be the first large payload put into orbit by the ‘space shuttle.’ Astronomers will be able to map the recessional velocities of galaxies to see if there are any irregularities in the Hubble expansion of the universe that could be evidence for a deceleration of expansion. Moreover, because of its ability to probe the universe to magnitudes 100 times fainter than can be reached from the ground, the telescope should reveal many new objects in other galaxies.”

In 1969 the National Academy of Sciences approved the Large Space Telescope project. The instrument was later renamed the Hubble Space Telescope and was launched in 1990.

NO-GROWTH ECONOMY?

“Two extreme positions have been established in the current debate on economic growth. Ronald C. Ridker of Resources for the Future suggests that both of them ‘are wrong—indeed, that they border on the irresponsible.’ The pro-growth school holds that material economic growth is the primary social goal, taking precedence over equity and measures to cope with the social and environmental costs of growth. The no-growth school seems to hold that social problems will disappear if growth ends. ‘The relevant question,’ Ridker says, ‘is not whether to grow or not to grow, but how to channel and redirect economic output … in ways that will better serve humanity’s needs.’ ”

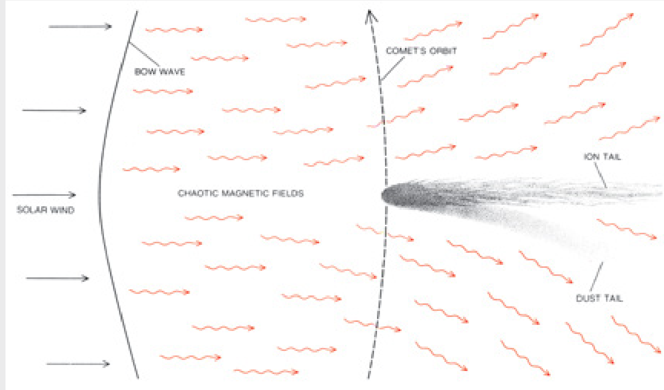


CURIOUS DINOSAUR EGGS FOUND

1924 “A few months ago a cablegram from China announced perhaps the most curious find ever made in exploration: a nest of dinosaur eggs—the first dinosaur eggs ever seen by a human being. Altogether 25 [fossilized] eggs were taken out. Examinations show that there were a number of species. In several eggs that had been broken in half there could be plainly detected the delicate bone of the embryos. Never before in science has it been possible to study paleoembryology. Baby dinosaurs that had probably been hatched only a few weeks, and others in all stages of growth up to the adults 10 feet long, were also discovered as fossil remains.”

ELEMENT 72: HAFNIUM

“The elements arranged in the order of atomic number showed a break after No. 71, lutecium, the last in the known series of rare earths. No. 72 was lacking. Dirk Coster and George de Hevesy, working in Copenhagen, deduced that the unknown element would probably show great resemblance to element No. 40, zirconium. The investigators examined the X-ray spectra of zirconium minerals and found, in addition to the characteristic lines of the element, lines of another, unknown element in the position where the lines of No. 72 should be. The two scientists succeeded in separating the new element, and named it in honor of Copenhagen (*Hafnia* in its Latin form).”



1974, Comet Explained: “Ion and dust tails are created by two processes. First, high-energy electrons in the solar wind ionize the molecules in the coma of the comet, stripping them of electrons and leaving them positively charged. Second, the solar wind gives rise to a bow wave around the coma; chaotic magnetic fields within the solar wind selectively carry the ionized molecules away from the coma at high speeds.”

RAILROAD TIME SET BY THE STARS

1874 “The extent of the U.S. forbids the adoption of one mean time for railroad use, found so convenient in Europe. It is therefore the practice, on our railroads, to run by Portland time, New York time, Altoona time or by the mean time of some other center of railroad traffic. The Pennsylvania Railroad and some of its dependencies, extending from New York to St. Louis, use Pittsburgh time, which is transmitted by electricity from the Allegheny observatory, an astronomical clock of the best construction. It is regulated by a telescope, which shows its return, every twenty-four hours, to the point of observation of a fixed star, so that the earth itself becomes the regulating clock of the observatory.”

LANDS UNKNOWN

“There is yet one seventeenth part of the globe of which we know nothing except by conjecture. The region which surrounds the south pole, the Antarctic, covers an area of 7,000,000 square miles. The Arctic measures nearly 3,000,000. The unexplored portion of Africa may be at least 1,000,000. The unknown part of Australia is certainly more than two thirds of that. Of the East Indian Archipelago, Borneo is considered the second-largest island on the globe. A strip along the coast of about 100 miles deep represents what we know of it; the interior remains unknown. So also of thousands of minute islands.”

Scientific American, Vol. 230, No. 2; February 1974


You're looking at me but are you really *seeing* me?
– Earth