JULY/AUGUST 2023

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The New Tornado Alley

Insect Sentience

Bringing Asteroid Bits Back to Earth

WHY PARROTS ARE TAKING OVER THE WORLD

JULY/AUGUST 2023

VOLUME 329, NUMBER 1

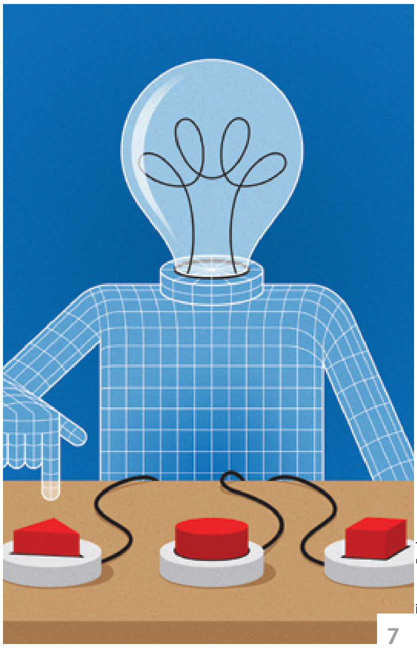
SCIENTIFIC AMERICAN

26

ON THE COVER
Parrots such as the Sulphur-crested Cockatoo are flourishing in cities all over the globe. At least 60 parrot species have populations well outside their natural geographical ranges, having been introduced to these locations by humans. For better or for worse, these smart, social birds are highly adaptable. **Photograph by Leila Jeffreys.**

Photograph by Levon Biss

SCIENTIFIC AMERICAN



Thomas Fuchs

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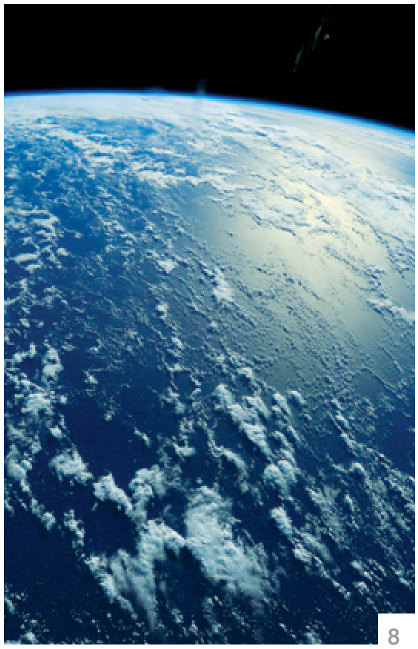

Samantha Cristoforetti/ESA/NASA

8

Wenjia Tang

88

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

The Minds of Others

Have you ever seen a parrot in a strange place? If you hear a flock of squawky, large and colorful birds and wonder if you're seeing things, you're not. Various species of parrots have escaped from the pet trade and have established thriving colonies in cities around the world—Sarasota, Fla.; New York City; Surprise, Ariz.; Singapore; Amsterdam; Tel Aviv—they're everywhere. It's hard not to anthropomorphize. As science writer Ryan F. Mandelbaum explains on page 40, they're smart, social, adaptable and assertive. They eat anything and breed anywhere. They're basically us with wings.

We're eagerly awaiting the return of NASA's OSIRIS-REx spacecraft in September. If all goes well, it will release its sample canister to blaze through the atmosphere, open a parachute and land in Utah carrying a scoop of material from the asteroid Bennu. Our space and physics editor Clara Moskowitz on page 34 narrates how the seven-year mission has progressed and what to expect next.

Scientists are finding treasure under the seafloor—unexpected, widespread aquifers of fresh water off coastlines worldwide. As coastal populations grow and stress existing water supplies, these deposits could be a good source of drinkable water. Geophysicist Rob L. Evans on page 58 shares how he helped to identify these aquifers and what we know about them so far.

Deadly tornado clusters are becoming more common in the U.S., and Tornado Alley is moving eastward. Our sustainability editor Mark Fischetti, with graphics by Matthew Twombly and a map by Daniel P. Huffman, shows us how, where and why tornadoes form and who is most at risk. Turn to page 70.

When you feel "in sync" with someone, that may reflect literal synchronized patterns in your brains. A new field of collective neuroscience is finding surprising similarities in people's brains as they interact, especially in pairs who have a close relationship or between effective teachers and their students. Our Science of Health columnist and contributing editor Lydia Denworth participated in a brain-scanning experiment to find out more (*page 50*).

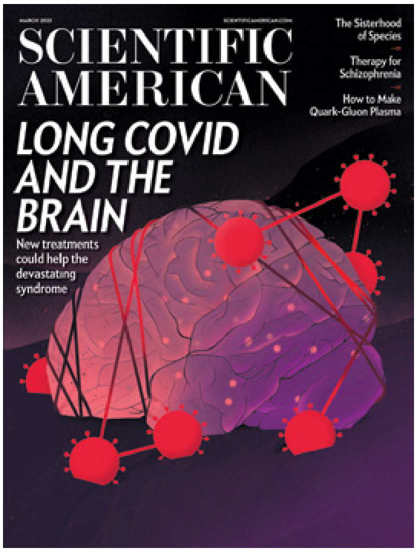
We'll probably never know exactly how the COVID-causing virus SARS-CoV-2 began circulating among people, but our health editor Tanya Lewis on page 76 recaps the evidence for the leading theory—a spillover from an infected animal, possibly in a Wuhan market in China—as well as the possibility of a lab leak.

What's it like to be a bee? Researchers have found that some insects are surprisingly intelligent. They can count, learn and teach, even feel pleasure and pain. Behavioral ecologist Lars Chittka on page 26 explores the implications of these intriguing discoveries.

Extreme heat events are the deadliest weather-related disasters in the U.S., but we tend to underestimate the risk. Researcher Terri Adams-Fuller on page 64 is experimenting with ways to warn and protect people, especially in urban heat island environments where temperatures rise much higher than in the suburbs.

In a delightful history of how ice inspired the modern cocktail, Amy Brady, our Reviews editor, describes how bartenders are now trying to change how they make and use ice. We hope you can read the article on page 82 sipping a refreshing cocktail or mocktail. And please enjoy this extra-long summer issue for July and August. Good luck staying cool and hydrated! SA

Illustration by Nick Higgins



March 2023

"This is one of the flaws of the cornucopians: they focus on benefits of innovations enjoyed by some while overlooking negatives experienced elsewhere."

RICHARD "DICK" FAHLMAN *TLA'AMIN NATION, BRITISH COLUMBIA*

COUNTER ARGUMENTS

In "Born to Count," Sam Clarke and Jacob Beck present several experiments that they assert demonstrate that humans are born with an innate "number sense." But not one of them indicates that the concept of, say, "eightness" is innate. What they instead show is that there is an innate inequality sense, an ability to distinguish which of two quantities is larger, provided that the difference between them is large enough.

Joel Sanet *via e-mail*

The various experiments Clarke and Beck describe demonstrate that young children have a concept of order. That is, they can put the elements of a set in order by some criterion. For example, a child may be able to put a golf ball, baseball, softball and soccer ball in order by size. The experiments do not show that these children can count.

Eric Klieber *via e-mail*

It seems that the property of thought that the article describes might better be called "generalized quantity," "comparative quantity" or "generalized cardinality." The term "number" doesn't seem appropriate for research on young children before they have developed either the ability to use a system of symbols or words associated with specific quantities or cardinalities—or at least before they know the sequence of number words "one, two, three …" or something equivalent.

In my own past research with young children, it seemed to me that their thinking about numbers was more closely related to Giuseppe Peano's basic concept of "successor" than cardinality or quantity. For example, if a kindergartener responded "five" to the question "How old are you?" the child would certainly not be able to remember far back enough to be conscious of their four birthdays prior to their fifth. To that child, the most important thing about "five" is that it is the successor of "four."

George E. Gullen III *Southgate, Mich.*

THE AUTHORS REPLY: Arguments that seek to debunk the innate number sense are tempting, but they struggle to fully explain the evidence. Sanet and Klieber propose that young children merely represent inequality and order, respectively, not number. Yet neither proposal can explain young children's ability to add and multiply, as described in our article. Meanwhile Gullen proposes that children merely represent generalized quantity. We were at pains to explain that the number sense is sensitive to properties that are unique to number, however—for instance, the description relativity isolated by Gottlob Frege.

Gullen observes that when children learn to use number words such as "one, two, three," they gain a novel appreciation for the successor relation. We agree. But it is a non sequitur to conclude that children don't represent number beforehand. Just as you can see how far away a tree is (thereby representing distance) before you learn to measure distance precisely with a ruler, you can see how many trees there are (thereby representing number) before you learn to count.

INEQUITABLE INNOVATION

In "The Eight-Billion-Person Bomb" [Observatory], Naomi Oreskes argues against cornucopianism, a theoretical framework that asserts that human ingenuity can overcome limited natural resources.

I would like to offer a point of confirmation that cornucopianism is misguided. On CBC Radio, I recently heard an interview describing the catastrophic effects of finding cobalt, a rare mineral needed for batteries, in the Democratic Republic of the Congo. To me, this illustrates one of the flaws of the cornucopians: they focus on benefits of innovations enjoyed by some while consciously or unconsciously overlooking negatives experienced elsewhere. This is a logical progression of the phenomenon of the past several centuries: global capitalism.

Richard "Dick" Fahlman
Tla'amin Nation, British Columbia

NATURAL CAPITAL IDEA

In "Use Nature as Infrastructure" [Science Agenda, April], the editors lay out the reasons why policy makers should be putting nature on the nation's balance sheet. The Biden-Harris administration wholeheartedly agrees. In January we released the *National Strategy to Develop Statistics for Environmental-Economic Decisions,* a historic effort to account for America's natural assets in our national economic statistics.

We're currently working to quantify the economic value of our natural capital, including the ocean and rivers that support our recreation and fishing industries, the forests that clean our air and water, the minerals that power our technology economy and drive the electric vehicle revolution, and much more. By expanding the national economic accounting system to include natural capital and by including services from ecosystems in benefit-cost and regulatory analyses, we will more accurately capture the links between nature and the economy—which will help guide policy and business decisions.

Both the Inflation Reduction Act and the Bipartisan Infrastructure Law include funding for nature-based solutions to climate change, such as protecting forests and restoring marshes to reduce greenhouse gas emissions, remove carbon from the atmosphere and lower the risks to people from extreme weather. President Joe Biden has taken additional action by signing executive orders that create a National Nature Assessment to better understand how nature is changing in the U.S.; quantify the impacts of climate change in the federal budget; and promote environmental services and opportunities for local economies across the country.

The Biden-Harris administration is working hard to maintain and invest in natural infrastructure. We're making sure that ecosystem services are considered at every level of government decision-making.

ELI FENICHEL, HEATHER TALLIS, SOLOMON HSIANG AND JANE LUBCHENCO
White House Office of Science and Technology Policy

EDITOR'S NOTE: Fenichel was at OSTP when this letter was submitted. He is now at Yale University.

FUNDAMENTALLY WEIRD

British geneticist J.B.S. Haldane (1892–1964) would have been delighted to read "Primordial Soup," by Clara Moskowitz. It raises the question of why the universe is so floridly strange and weird at all scales. At large scales, we see stars, galaxies, supernovae and black holes; at medium scale, we see molecules, DNA, proteins, molecular machinery and life itself.

And now the tiny, pristine sphere of positive charge of my physics education has become a sea of quarks and antiquarks with three valence quarks bobbing on its surface, all held together by gluons. I, too, am delighted.

JOHN COENRAADS
Victoria, British Columbia

ERRATA

"A Hidden Variable behind Entanglement," by Michelle Frank [April], incorrectly gave Emilio Segrè's first name as "Emile."

In "The Sisterhood of Species," by Barbara Natterson-Horowitz, the box "Under Pressure" incorrectly depicts the right atrium of the heart. The corrected illustrations can be found at https://www.scientificamerican.com/article/what-scientists-are-learning-about-womens-health-from-other-female-animals

Kids Need Better Places to Play

To get children moving more, we must invest in safe areas for outdoor fun

By the Editors

The rate of childhood obesity in the U.S. has tripled over the past 50 years. But what this trend means for children's long-term health, and what to do about it (if anything), is not so clear.

The American Academy of Pediatrics (AAP) made waves this year by recommending that doctors put obese kids as young as two years old on intensive, family-oriented lifestyle and behavior plans. It also suggested prescribing weight-loss drugs to children 12 and older and surgery to teens 13 and older. This advice marks a shift from the organization's previous stance of "watch and wait," and it reflects the AAP's belief that obesity is a disease and the group's adoption of a more proactive position on childhood obesity.

Yet the lifestyle programs the AAP recommends are expensive, inaccessible to most children and hard to maintain—and the guidelines acknowledge these barriers. Few weight-loss drugs have been approved for older children, although many are used off-label. They have significant side effects for both kids and adults. And surgery, while becoming more common, has inherent risks and few long-term safety data—it could, for instance, cause nutritional deficits in growing children. Furthermore, it's not clear whether interventions in youngsters help to improve health or merely add to the stigma overweight kids face from a fat-phobic society. This stigma can lead to mental health problems and eating disorders.

Rather than fixating on numbers on a scale, the U.S. and countries with similar trends should focus on an underlying truth: we need to invest in more and safer places for children to play where they can move and run around, climb and jump, ride and skate.

Moving more may not prevent a child from becoming overweight, but studies show clearly that it helps both physical and mental health. In 2020 the Centers for Disease Control and Prevention found, unsurprisingly, that kids' sports participation increases with their parents' incomes: about 70 percent of kids whose families earn more than $105,000 a year participate in sports, but only 51 percent of middle-class kids and 31 percent of children at or below the poverty line do. This disparity hurts people of color the most. More than 60 percent of white children, for instance, participate in athletics, but only 42 percent of Black children and 47 percent of Hispanic children do. Experts blame these problems on the privatization of sports—as public investment in school-based athletics dwindles, expensive private leagues have grown, leaving many kids out.

According to the U.S. Department of Health and Human Services' Physical Activity Guidelines for Americans, children between ages six and 17 should get at least an hour of moderate to intense physical activity every day. Yet only 21 to 28 percent of U.S. kids meet this target, two government-sponsored surveys found. The nonprofit Active Healthy Kids Global Alliance evaluates physical activity in American children, and in 2022 the group gave the U.S. a grade of D–.

Why is it so hard to get kids moving? In addition to fewer opportunities at school, researchers cite increased screen time, changing norms around letting kids play outdoors unsupervised, and a lack of safe places for them to play outside the home.

New York City, for example, had 2,067 public playgrounds as of 2019—a "meager" amount for its large population, according to a report from the city comptroller—and inspectors found hazardous equipment at one quarter of them. In Los Angeles in 2015, only 33 percent of youths lived within walking distance of a park, according to the L.A. Neighborhood Land Trust. Lower-income neighborhoods tend to have the fewest public play spaces, despite often having a high population density. And although rural areas have more undeveloped outdoor space, they often lack playgrounds, tracks and exercise facilities.

Kids everywhere need more places to play: trails, skate parks and climbing walls, gardens and ball fields, bike paths and basketball courts. Robust public funding to build and keep up these areas is crucial, but other options such as shared-use agreements can make unused spaces available to the public. Only 10 percent of U.S. schools let people into their playgrounds and schoolyards when school's out, the Trust for Public Land found, and opening up these spaces would give 5.2 million more children access. "Play streets"—residential streets or parking lots that are temporarily closed for activities—are another affordable way to give kids more chances to run around.

These opportunities aren't primarily about changing children's waistlines—they're how we keep childhood healthy and fun. SA

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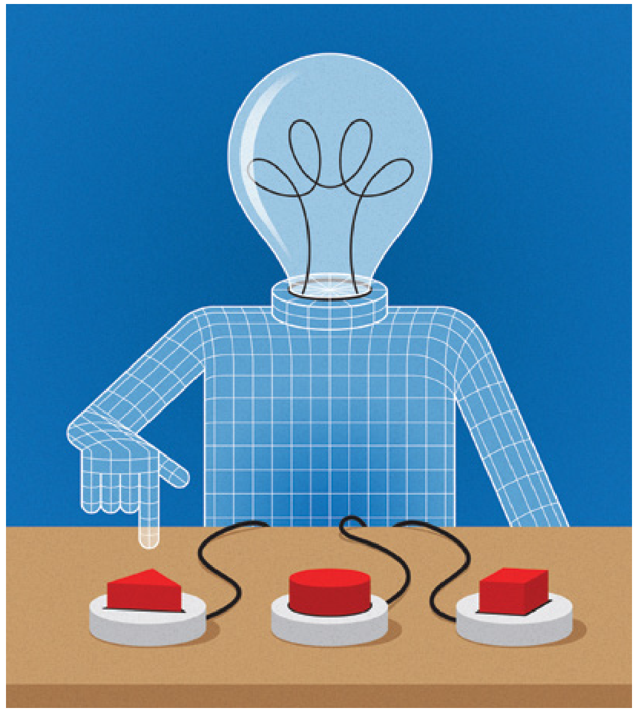
Illustration by Luisa Jung

Eka Roivainen is an assessment psychologist at Oulu University Hospital in Finland. His research interests include cognitive and personality psychology and the validity of psychological testing.

AI's IQ

ChatGPT aced a test but showed that intelligence cannot be measured by IQ alone

By Eka Roivainen



ChatGPT is the first nonhuman subject I have ever tested in my work as a clinical psychologist. I assess the cognitive skills of humans by administering standardized intelligence tests. After reading recent articles describing ChatGPT as having impressive, humanlike skills—writing academic essays and fairy tales, telling jokes, explaining scientific concepts, and composing computer code—I was curious to see how smart ChatGPT was by human standards.

The text-generating AI system was almost an ideal test taker. It didn't show test anxiety, poor concentration or a lack of effort. Nor did it express uninvited, skeptical comments about intelligence tests and testers like me.

I used the third edition of the Wechsler Adult Intelligence Scale (WAIS-III) and selected five of its six verbal IQ subtests to estimate ChatGPT's IQ. I started with the WAIS Vocabulary subtest because I expected it to be easy for the chatbot, which is trained on vast amounts of online text. This subtest measures word knowledge and verbal concept formation. A typical instruction might read, "Tell me what 'gadget' means." The test taker would receive one point for a basic answer such as "a thing like my phone" and two points for something more detailed—for example, "a small device or tool for a specific task." ChatGPT aced the subtest, receiving the full two points on each question.

The chatbot also earned the maximum score on the Information subtest, which covers general knowledge and examines the subject's intellectual curiosity, level of education, and ability to learn and remember facts. A typical question in this section might be, "What is the capital of Ukraine?" And ChatGPT breezed through the Similarities subtest, which measures abstract reasoning and concept-formation skills with questions such as, "In what way are Harry Potter and Bugs Bunny alike?" In this subtest, the chatbot's tendency to give very detailed, show-offy answers started to irritate me. For this question there was no need for ChatGPT to go beyond the fact that they are both fictional characters, but it delivered their complete histories of adventures, friends and enemies. Here the "stop generating response" button of the test software interface turned out to be useful.

On the Comprehension section, ChatGPT correctly answered questions such as, "If your TV set catches fire, what should you do?" And as expected, the chatbot solved all the problems it received in the Arithmetic portion, sailing through questions that required, say, taking the average of three numbers.

So what did it score? On five subtests the verbal IQ of ChatGPT was 155—better than 99.9 percent of the test takers who make up the U.S. WAIS-III standardization sample. The mean score among college-educated Americans is 113; only 5 percent score 132 or higher. I myself was tested by a peer and did not quite reach the level of ChatGPT, mainly because my brief answers lacked detail.

Does this mean the jobs of clinical psychologists and other professionals threatened by AI? Not yet. Despite its high IQ, ChatGPT fails at tasks that require real humanlike reasoning or an understanding of the physical and social world. It flubs obvious answers to riddles such as "What is the first name of the father of Sebastian's children?" Its response this past March was: "I'm sorry, I cannot answer this question as I do not have enough context to identify which Sebastian you are referring to." ChatGPT seemed unable to reason logically and tried to rely on its vast database of "Sebastian" facts derived from online texts.

"Intelligence is what intelligence tests measure" is a classical definition by a pioneer of cognitive psychology, Edwin G. Boring. This definition is based on the observation that skills needed for seemingly diverse tasks such as solving puzzles, defining words, doing arithmetic problems and spotting missing items in pictures are highly correlated. Psychologist Charles Spearman, developer of a statistical method called factor analysis, concluded that a general factor of intelligence, called a *g* factor, must underlie the concordance of measurements for various human cognitive skills. IQ tests such as WAIS are based on this hypothesis.

The combination of ChatGPT's very high verbal IQ and its amusing failures, however, means trouble for Boring's definition and indicates there are aspects of intelligence that cannot be measured by IQ tests alone. Perhaps my test-skeptic patients have been right all along.

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Illustration by Thomas Fuchs

M. Scott Brauer/MIT/UPI/Alamy

THE DARK UNIVERSE COMES INTO FOCUS

The LIGO experiment opened a whole new window to the universe. We asked Rainer Weiss, one of LIGO's lead architects, what gravitational-wave astronomy could reveal next.

About a billion years ago, a pair of black holes 30 times the mass of our sun whirled around one another, drawing closer and closer. When they ultimately crashed together, the force of their collision sent shock waves skittering across the very fabric of space.

On September 14, 2015, an instrument called LIGO picked up the remnants of those ripples. The discovery of these gravitational waves provided solid proof of Einstein's theory of general relativity, which predicted their existence more than a century ago. And it heralded the dawn of a new era of astronomy.

The gravitational waves LIGO detected distorted the geometry of space-time by just 10^{-18} meter—a thousandth the width of the nucleus of an atom—and it registered here on Earth as a brief and gentle chirp. But detecting this previously unseen class of signals provides a new way of observing the cosmos, allowing us to tune in to collapsing stars, battling black holes and the universe itself.

Sensing such tiny stirrings in space-time required experimental breakthroughs, unflagging effort and four decades of high-tech troubleshooting, and it earned Rainer Weiss, Kip Thorne, and Ronald Drever the 2016 Kavli Prize in Astrophysics, followed by a Nobel Prize for Weiss and Thorne. It also gave them a front-row seat to the most epic astronomical pas de deux the world has ever witnessed.

Scientific American Custom Media sat down with Weiss to hear about the secrets and surprises he thinks gravitational astronomy is bound to reveal, including the nature of dark matter, the origin of the first black holes, and the events that transpired when the universe winked into existence.

Where do we go from LIGO?

To boost the sensitivity of our instruments by a factor of 10, we want to build the Cosmic Explorer, which has 40-kilometer arms—10 times longer than LIGO's. Europeans will be building the Einstein telescope, which will be a triangle with 10-kilometer sides and three detectors, each with interferometers that can be tuned to different [gravitational-wave] frequencies. These longer antennae should be able to tune in to all the binary black holes in the universe that have come from the collapse of stars, as well as all the colliding neutron stars. The European Space Agency is also developing LISA—a space-based triangle of interferometers with arms about 1.5 million kilometers long that will hopefully launch in the 2030s. It will allow us to see—or hear—the collision of gigantic black holes that are a million solar masses, like the one at the center of our galaxy, and watch as they eat a smaller black hole, or even a star. It will be fascinating.

How do black holes form?

The most likely way is in a supernova, the end result of the collapse of a star. But we expect that nature can also make black holes by distorting space. This should make gravitational waves. It should distort and excite geometry, like a hammer to a xylophone, and make space-time ring. People have imagined these things over the years, but with Cosmic Explorer or LISA, we want to see them for real.

What exactly is dark matter?

I happen to think that dark matter is made of black holes—really small black holes, a tiny fraction of a solar mass, that don't interact much with light so you can't see them. The distribution of hot spots and cold spots we see in the cosmic microwave background radiation could not have existed unless there was dark matter holding those places together somehow. So dark matter's been around since the beginning of time. And I think that black holes that form from distortions in the geometry of space are as good a candidate as anybody has right now.

What can neutron stars teach us about physics and chemistry?

People always wondered where in the universe you could create heavy elements like gold or platinum. Turns out it's through neutron star collisions. Neutron stars pack the weight of the sun into the size of a city, and they're made primarily of neutrons. When they crash into each other, they produce an afterglow called a kilonova, which is a plasma made of the most fundamental particles you can think of: gluons and quarks, things we see in atomic nuclei.

After LIGO detected the first neutron binary merger in 2017, people studied its kilonova. They identified broad [spectral] signatures for elements like gold and platinum. Looking at more of these collisions, we're going to learn a lot about the fundamental interactions between particles. We don't have an accelerator powerful enough to produce this kind of plasma on Earth, so that's going to be a big deal.

How did the universe come to be?

According to [cosmic inflation theory], the universe was created by a fluctuation in the vacuum. That kind of fluctuation will have instabilities and explode asymmetrically—which will generate gravitational waves. Those primordial gravitational waves, produced at the instant of creation, are still with us, still there to be measured. They're too weak to be seen directly by any instrument being considered for the near future. But we might be able to measure them indirectly, based on how they polarize the cosmic microwave background radiation. Those experiments are ongoing. Detecting the primordial gravitational waves from the instant of creation—that would tell us about the origin of everything. And what could be more important than that?

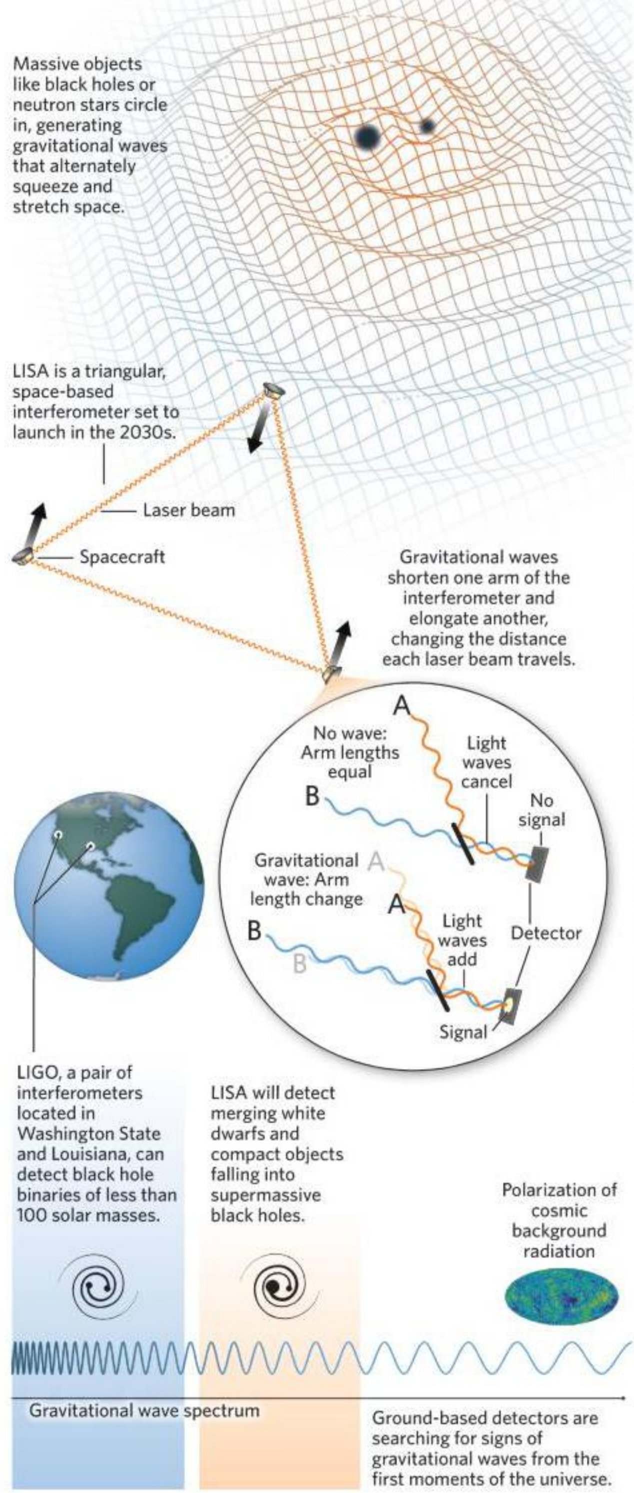
What surprises might the universe still have in store for us?

When we start looking with new and more sensitive instruments, better instruments, we turn up all sorts of surprises. That's happened over and over again in astronomy. Now, gravitational waves are showing us things we've never seen. The thing I'm really counting on is that we'll find things we never even imagined in signals that come from the universe itself. *That's* what's driving me.

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

WHAT GRAVITATIONAL WAVES REVEAL

Gravitational waves provide a way of listening to the universe, from the ringing of colliding black holes to the background hum of the big bang.



SOURCE: LISA mechanism: R. Weiss; Cosmic microwave background image: NASA / WMAP Science Team.

THE KAVLI PRIZE

ADVANCES

Earth's abundant water makes an impression from space, but its origins are not fully understood.

Samantha Cristoforetti/ESA/NASA

INSIDE

PLANETARY SCIENCE

Aqua Earth

Exploring where Earth got its water

In the last hours of the last day of February 2021, a 29-pound chunk of space rock ripped into Earth's upper atmosphere at roughly 8.5 miles per second. As it streaked through the stratosphere, the heat and friction of entry charred its exterior a deep black. Bits of soft rock sloughed off in the blaze, and a huge fireball briefly flared like a torch in the night sky.

By the time the largest piece of debris landed abruptly in a driveway in Winchcombe, England, it weighed only 11.3 ounces. Scientists snagged the rocky, powdery material within 12 hours, making it among the freshest meteorites ever studied. "It's pretty much as pristine as we're going to get," says Ashley King, a planetary scientist at the Natural History Museum in London.

The Winchcombe meteorite belongs to a rare class of space rocks known as carbonaceous chondrites. These volatile bodies are helping researchers piece together one of the biggest puzzles on Earth: where our planet's water came from. Researchers think some may have arrived on meteorites, but how much is hotly debated. Some argue that meteorites made it rain; others say their contribution may have been more like a drop in the bucket.

Before Earth was a planet, it was a cloud of dust orbiting the young sun. Through a process called accretion, this dust condensed to form pebbles that collided and stuck together. The impacts produced increasingly large rocks, which eventually snowballed into a whole planet.

Early Earth was not the "pale blue dot" of today; its temperatures spiked to 3,600 degrees Fahrenheit, more than enough to boil any surface water off into space. Scientists once believed this meant the planet would have been bone-dry in its infancy, but recent research published in *Nature* suggests it might have been significantly wetter. After noting that numerous Earth-like exoplanets were blanketed with a hydrogen-rich atmosphere as they accreted, study co-author Anat Shahar, a geochemist at the Carnegie Institution for Science in Washington, D.C., and her colleagues simulated Earth's formation with such an atmosphere added. They discovered that, contrary to previous hypotheses, lots of water endured in the virtual planet's atmosphere and became encased inside its rocky mantle, even as magma rivers flowed freely across the outer crust.

Although this model suggests that considerable water could have been here since the planet formed, planetary geologists remain confident that a significant portion still came from beyond our atmosphere. "There's so much evidence," Shahar says. "We can't argue against it."

The "smoking gun," King says, is hidden in Earth's hydrogen. Hydrogen exists on Earth in two stable "flavors," called isotopes: regular hydrogen, which has a single proton for its nucleus, and deuterium, whose nucleus is made of one proton and one neutron. Water found in the mantle has about 15 percent less deuterium than seawater; that extra seawater deuterium most likely came from somewhere else.

Astronomers initially theorized that deuterium-rich water traveled to Earth on comets. Because they exist in the solar system's cold outer reaches, comets are extremely icy; up to 80 percent of their mass may be water. But in 2014 data from the European Space Agency's Rosetta mission showed that many comets' isotopic ratio is way off—they have far more deuterium than terrestrial water does. Scientists proposed another hypothesis: water surfed into our atmosphere on the solar wind, which pushes free-range hydrogen and oxygen molecules from space toward Earth. Many scientists maintain, however, that these molecules' deuterium ratio is far too low. "It's hard to explain the water budget from those sources," says Megan E. Newcombe, a petrologist at the University of Maryland.

So where was the Goldilocks isotope ratio? Researchers finally hit the jackpot with asteroids—specifically, raw asteroid chunks called chondrites. Carbonaceous chondrites, which are named for their carbon content, are up to 20 percent water. "This doesn't mean that when you touch the meteorite, it's wet," says Maria Valdes, a geologist at the Field Museum in Chicago. Instead they carry the atomic ingredients for water: a 2:1 hydrogen-to-oxygen ratio.

For a 2022 paper in *Science Advances*, King and his colleagues analyzed the Winchcombe meteorite using spectroscopy. They found that the meteorite's deuterium-

TECH

Electric Healing

New bandage zaps and medicates chronic wounds

Some wounds won't heal by themselves. These lesions, which include certain diabetic ulcers, burns and surgical injuries, cause long-term suffering and can linger indefinitely if not successfully treated. They sometimes become infected and in extreme cases turn fatal.

Current chronic wound therapies often require surgery or lead to overuse of antibiotics, which can worsen the problem of antibiotic-resistant bacteria. "Chronic wounds affect tens of millions of people," says California Institute of Technology biomedical engineer Wei Gao. "There's an urgent need for personalized wound treatment."

For a study published in *Science Advances*, Gao and his colleagues used rodents to test a "smart bandage" that could make chronic wound healing easier and faster. It consists of a stretchable polymer patch that adheres to the skin, containing medication and a thin layer of electronics that monitors and wirelessly transmits data about the wound's

condition. The patch can carry out controlled delivery of two treatments: a drug and an electric current.

The bandage builds on previous efforts to promote healing with electricity. This process, called electrotherapy, works both by attracting immune cells and skin cells to the wound and by boosting cell growth and division. A study published last year led by engineer Yuanwen Jiang, now at the University of Pennsylvania, described a bandage that monitored temperature and conductivity, using the collected data to control delivery of electrotherapy.

The new research adds biochemical sensing capabilities. In addition to temperature and pH, the bandage's biosensor monitors levels of ammonium, glucose, lactate and uric acid; together these measurements provide information about inflammation, infection and stage of healing. "Biochemical signals open up new opportunities because you're able to really probe what's happening on a molecular level," Jiang says. "That's the key novelty here." Gao and his colleagues also added an electroactive gel that releases an anti-inflammatory, antimicrobial drug when stimulated by an electrode. Another electrode stimulates the wound directly.

The team tested the bandage on rodents with diabetic wounds and found that it accurately detected changes in inflammatory and metabolic states at different stages of wound healing. The bandage's combined treatments fully healed rodent wounds in two weeks. Each individual treatment achieved at least partial healing within that time, and untreated animals did not heal.

Researchers still need to investigate the bandage's biosensor durability in human patients' chronic wounds. "Requirements for the lifetime of the device are very different between rodents and human subjects," Jiang says. "Stability over that extended period has not been tested yet."

As they head toward human testing, the team is working to improve accuracy and stability. "We hope to apply this smart bandage technology in humans in the next year," Gao says. "Hopefully the information we get can really benefit people with chronic wounds." —*Simon Makin*

California Institute of Technology

to-hydrogen ratio matched Earth's oceans almost perfectly—an especially notable result given how quickly they collected it.

"Meteorites don't like the atmosphere," says Denton Ebel, geology curator at the American Museum of Natural History. The minerals inside space rocks soak up water vapor like a sponge as soon as they hit the air. But because the Winchcombe sample was obtained within 12 hours of impact, it was much less contaminated with terrestrial water than most samples.

A few months after the Winchcombe analysis came out, a study by Newcombe and her team further strengthened carbonaceous chondrites' case. For that paper, published this year in *Nature*, they analyzed several newly fallen meteorites from a group called the achondrites. Unlike carbonaceous chondrites, these meteorites come from asteroids or other rocky bodies that have been partially melted by radiation and geologic processes. Newcombe and her coauthors found that the melting process stripped achondrites of their moisture, like baking cookie dough. "Everything we found, whether it came from the inner or the outer solar system, was really, really dry," she says.

But this discovery doesn't mean carbonaceous chondrites were the planet's only water carriers, notes Laurette Piani, a cosmochemist at the University of Lorraine in France. "In my opinion, there are probably several sources for water on Earth," she says. It would take an awful lot of meteorite impacts to account for the planet's oceans in chondrites alone, and carbonaceous chondrites are fairly rare today. Piani points out that roughly equal parts solar wind, comets, water bubbling up from the mantle and chondrites could be combined to match Earth's isotope balance. Whatever the exact recipe for Earth's water, investigating its origin will reveal more about how our planet formed and became the dynamic blue world we live in. —*Joanna Thompson*

EVOLUTION

Munching Bugs

How insect eating gave early mammals a toothy edge

More than 220 million years ago, as early dinosaurs were just getting their legs under them, the first mammals evolved from a group of tiny, weasel-like reptiles called cynodonts. New research hints that mammals' huge success later on may be linked to a surprisingly small dietary choice: insects.

As cynodonts evolved into early mammals, they developed fewer teeth and skull bones. Paleontologists had long assumed these simplifications allowed for stronger skulls and multiple tooth types, letting mammals benefit from a greater variety of foods. Yet no one knew exactly what drove these changes, and now a study in *Communications Biology* has added a new facet to the story.

"The transition from cynodonts to mammals is a textbook example of repurposing existing skeletal elements," says lead author Stephan Lautenschlager, a paleontologist at the University of Birmingham in England. In their study, Lautenschlager and his colleagues used digital models and biomechanical tests to investigate how the simpler early-mammal skulls held up to biting stresses. Rather than finding increased efficiency or stress resistance in general, they learned that the stress of simulated bites decreased across the top of the skull but increased along the cheek. The specific patterns, and the earliest mammals' relatively small size, are reminiscent of modern small insectivores—which use quick bites and a dental tool kit of puncturing and crushing teeth to bust through arthropod carapaces.

"These findings suggest the patterns we see in the evolution of mammal skulls are more nuanced than we might have thought," says Oxford University Museum of Natural History paleontologist Elsa Panciroli, who was not involved in the new research. "This study gives us fresh data to start getting closer to the answers."

The insect-munching specialists' anatomical changes set the stage for mammal evolution through to today, the researchers say. The changes provided a foundation for later adaptations to feed on plants and larger animals; over time these pioneers became the Mesozoic equivalents of otters, raccoons, flying squirrels and aardvarks. "It's not about how hard you can bite," Panciroli says, "but perhaps about the different ways in which you can bite and chew." —*Riley Black*

ROBOTICS

Sight Unseen

Robot rotates complex objects using only touch

Many robots track objects by "sight" as they work with them, but optical sensors can't take in an item's entire shape when it's in the dark or partially blocked from view. Now a new low-cost technique lets a robotic hand "feel" an unfamiliar object's form—and deftly handle it based on this information alone.

University of California, San Diego, roboticist Xiaolong Wang and his team wanted to find out if complex coordination could be achieved in robotics using only simple touch data. The researchers attached 16 contact sensors, each costing about $12, to the palm and fingers of a four-fingered robot hand. These sensors simply indicate if an object is touching the hand or not. "While one sensor doesn't catch much, a lot of them can help you capture different aspects of the object," Wang says. In this case, the robot's task was to rotate items placed in its palm.

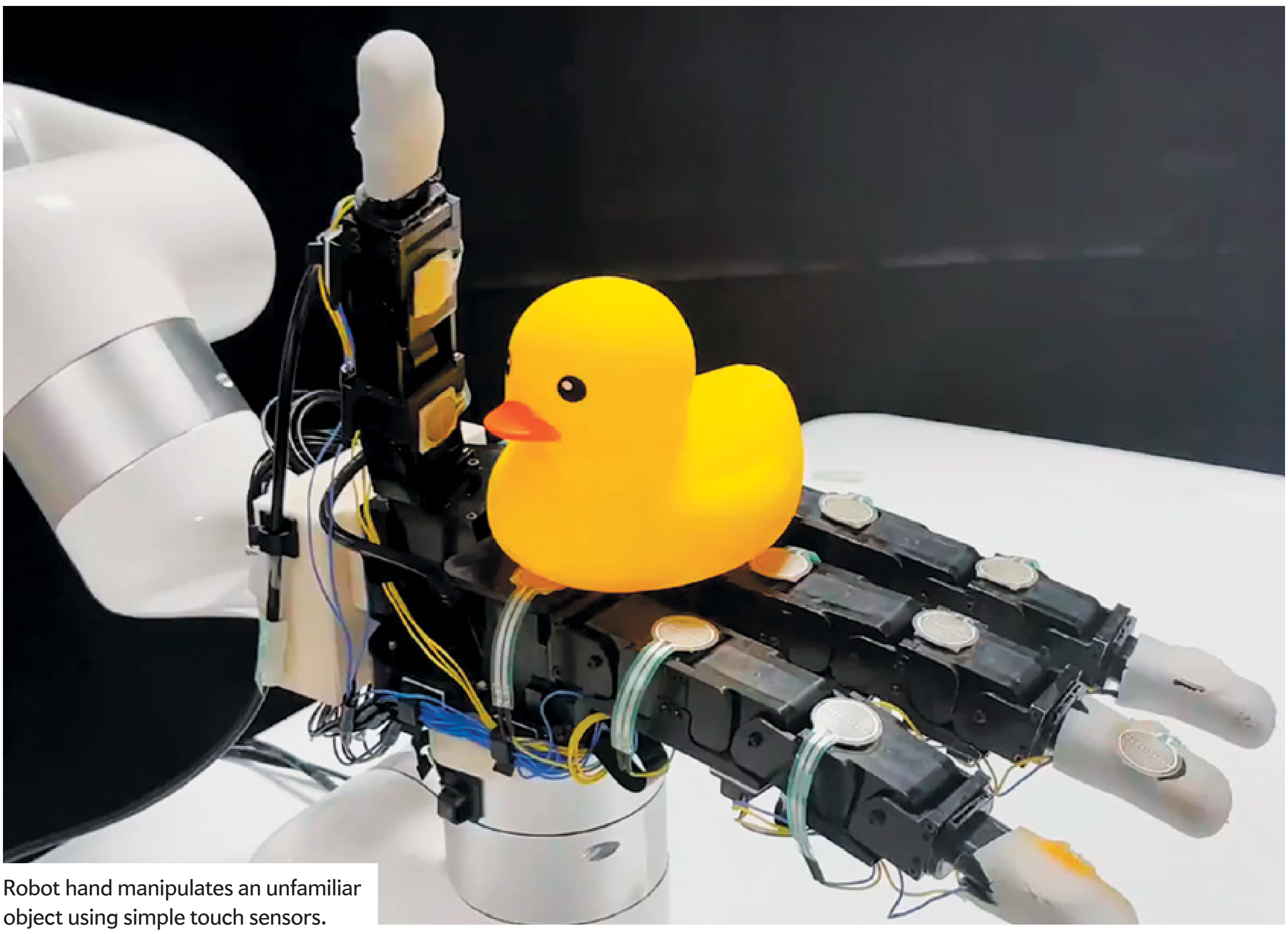
The researchers first ran simulations to collect a large volume of touch data as a virtual robot hand practiced rotating objects, including balls, irregular cuboids and cylinders. Using binary contact information ("touch" or "no touch") from each sensor, the team built a computer model that determines an object's position at every step of the handling process and moves the fingers to rotate it smoothly and stably.

Next they transferred this capability to operate a real robot hand, which successfully manipulated previously unencountered objects such as apples, tomatoes, soup cans and rubber ducks. Transferring the computer model to the real world was relatively easy because the binary sensor data were so simple; the model didn't rely on accurately simulated physics or exact measurements. "This is important since modeling high-resolution tactile sensors in simulation is still an open problem," says New York University's Lerrel Pinto, who studies robots' interactions with the real world.

Digging into what the robot hand perceives, Wang and his colleagues found that it can re-create the entire object's form from touch data, informing its actions. "This shows that there's sufficient information from touching that allows reconstructing the object shape," Wang says. He and his team are set to present their handiwork in July at an international conference called Robotics: Science and Systems.

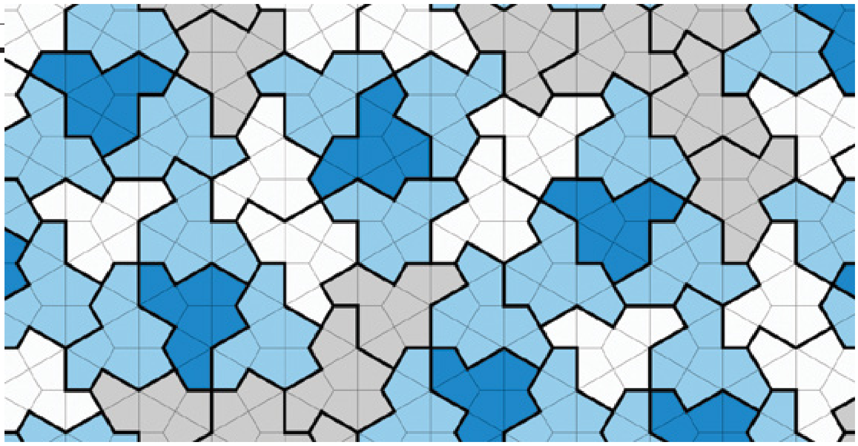
Pinto wonders whether the system would falter at more intricate tasks. "During our experiments with tactile sensors," he says, "we found that tasks like unstacking cups and opening a bottle cap were significantly harder—and perhaps more useful—than rotating objects."

Wang's group aims to tackle more complex movements in future work as well as to add sensors in places such as the sides of the fingers. The researchers will also try adding vision to complement touch data for handling complicated shapes. *—Ananya*



Robot hand manipulates an unfamiliar object using simple touch sensors.

Binghao Huang



David Smith, Joseph Samuel Myers, Craig S. Kaplan and Chaim Goodman-Strauss (CC BY-SA 4.0)

MATHEMATICS

Simply Infinite

New "einstein" tile intrigues the math world

David Smith, a math hobbyist in Yorkshire, England, has discovered a 13-sided shape that eluded mathematicians for decades. The craggy, hatlike shape is called an "einstein," based on the German for "one stone." If you used einstein-shaped tiles to cover your bathroom floor—or any flat surface, even if infinitely large—they would fit together perfectly but never form a repeating pattern. For decades mathematicians have been hunting for tile shapes like these that can form only nonrepeating arrangements, called aperiodic tilings. They started with sets of many different tiles: the first set, discovered in 1964, required 20,426 distinct tiles, which was later simplified to 103. By 1974 mathematician Roger Penrose had found two tile shapes that, when combined in a mosaic, never formed a repeating pattern.

But was it possible to form an aperiodic tiling with tiles of only *one* shape—the hypothetical einstein? Doris Schattschneider, a retired mathematician affiliated with Moravian University with expertise in tessellations, had been skeptical about the likelihood of a true einstein ever being discovered. "That's why it was so startling that not only was this found, but it's such a simple tile," she says. "To me, it's a total anomaly." The tile Smith discovered in November 2022, while he was experimenting with different shapes using a software called PolyForm Puzzle Solver, was astonishing in its elegance. Made up of right-angled kites, it was nothing like the gnarly, complicated kind of shape many mathematicians would have predicted.

Smith e-mailed Craig Kaplan, a computer scientist at the University of Waterloo in Ontario, who recognized the shape's potential. Although the mosaic it created seemed not to have a repeating pattern, the duo needed to mathematically prove it never would—even if the mosaic were infinitely large. They enlisted software developer Joseph Samuel Myers and University of Arkansas mathematician Chaim Goodman-Strauss, who had both worked with tiling and combinatorics in the past.

The researchers used two methods to prove they had a genuine einstein on their hands. First, they showed that the hatlike tiles, when arranged together, formed four specific kinds of shapes. Adding more tiles forms even bigger versions of those same shapes, or "supertiles;" the more tiles added, the bigger the supertiles become. Mathematicians have proved that this hierarchical structure means the tiling can't be split into repeating sections and thus must be aperiodic. For the second proof, the team invented a new method that could compare the hat tilings with the nonperiodic tilings of better-known shapes called polyiamonds. In the process, the team also showed that one could make an infinite number of similar einsteins by tweaking some of the sides' lengths.

Even with these proofs, mathematicians haven't yet formulated a broader theory for what makes this simple hat shape so special. "This is still very mysterious," says mathematician Rachel Greenfeld of the Institute for Advanced Study in Princeton, N.J. There may be more classes of einstein tiles out there, waiting to be discovered, but the geometric hat isn't revealing any clues, says Marjorie Senechal, a retired mathematician affiliated with Smith College: "These things you stumble upon."

—*Manon Bischoff and Allison Parshall*

SUSTAINABILITY

Waste Not

How food waste threatens the planet

Around a third of human-generated greenhouse gas emissions comes from the global food system, and lost or wasted food is known to contribute some amount—but it has never been clear to exactly what degree. Now, by following specific foods through their entire life cycle, researchers have determined just how much this wasted food adds to emissions through phases such as harvest, transportation and disposal.

For a study in *Nature Food*, Xunchang Fei of Singapore's Nanyang Technological University and his colleagues used 164 countries' food supply data from 2001 to 2017 to estimate emissions across 54 food commodities and four categories: cereals and pulses; meat and animal products; vegetables and fruits; and root and oil crops.

Roughly a third of food is lost during harvest, storage and transportation or is wasted by consumers. The team found this food was responsible for greenhouse gases equivalent to 9.3 billion metric tons of carbon dioxide—about half the global food system's total emissions—in 2017. Four countries (China, the U.S., India and Brazil) contributed 44.3 percent, mainly owing to their dietary habits and large populations. Of the four food categories, meat and animal products were the source of almost three quarters of emissions that occurred during the supply-chain phase for food that was ultimately lost.

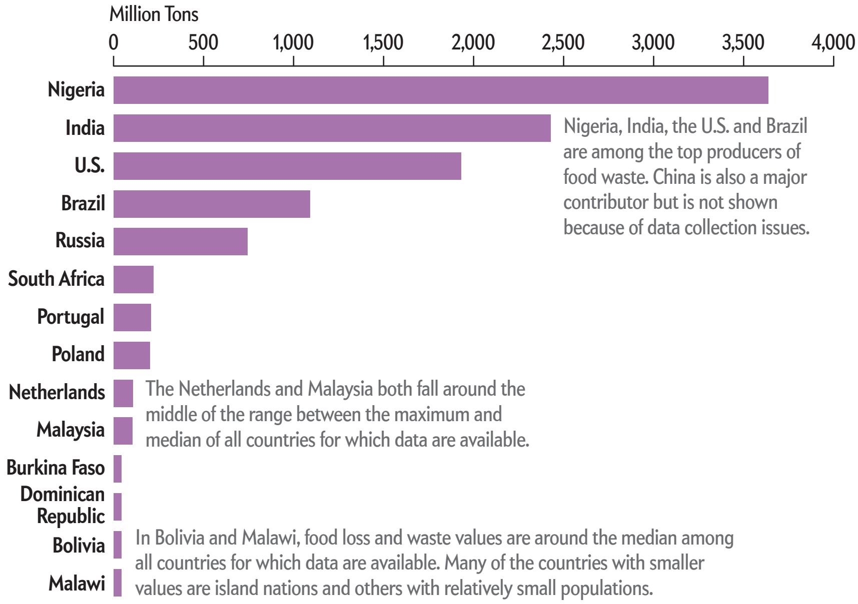
The study considered emissions across nine postfarming stages, which vary among regions—for instance, developed countries' advanced waste-treatment technologies can create fewer emissions. Such intricate details show how "different countries should set different targets for [food loss and waste] reductions," Fei says—such as reducing meat production in some areas, and switching from landfills to anaerobic digestion or composting processes in others.

Food systems expert Prajal Pradhan of the Potsdam Institute for Climate Impact Research in Germany notes that the United Nations Sustainable Development Goals aim to halve food waste in the coming years—which Pradhan says wouldn't be enough to limit global warming but would be a start. Based on this study, he says, emissions could decrease if "high-income countries could focus on saving food discarded by consumers, and low- and middle-income countries could prioritize avoiding food loss during harvesting, processing, storage and transport."

—Deepa Padmanaban

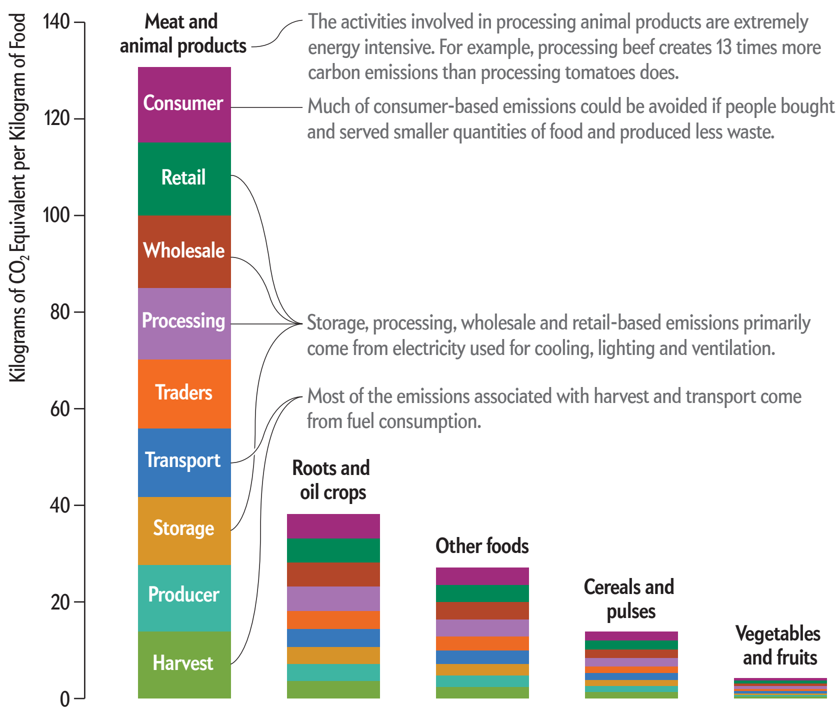
Food Loss and Waste by Country

The chart below shows how much food was lost and wasted in 2017 in a sampling of countries.



Greenhouse Gas Emissions by Food Type

The chart below shows how much greenhouse gas is produced on average during each step of the food supply chain for each category of food commodity. These values apply to the food supply chain as a whole and are not specific to food loss and waste.



Source: "Cradle-to-Grave Emissions from Food Loss and Waste Represent Half of Total Greenhouse Gas Emissions from Food Systems," by Jingyu Zhu et al., in *Nature Food*, Vol. 4; March 2023 (*data*)

Graphics by Jade Khatib

B. O'Kane/Alamy Stock Photo

PSYCHOLOGY

Feeling It

"Art" may be in the body of the beholder

If you feel deeply stirred by Edward Hopper's painting *Nighthawks* but unmoved passing by a real-world diner late at night, it may be because of what's happening inside your body. New research published in *Cognition and Emotion* suggests that bodily sensations aren't just a by-product of art's emotional impact but a key pathway for experiencing something as "art" in the first place.

In a study involving 1,186 participants and 336 visual art pieces, researchers found that the strength of emotional experience triggered by an artwork correlated with the strength of bodily sensations reported while viewing it. Emotions were measured using subjective reports, and viewers separately marked on a virtual human figure where and how they felt physical sensations. Eye tracking and participant surveys, meanwhile, gauged viewers' interest in the paintings and whether they considered them to be art.

Bodily feelings' magnitude correlated with both the strength of emotional experience and the evaluation of a piece as art. Sensations were most prominent when participants said they felt empathy (the most commonly reported positive emotion) and when they cited "touching" and "moving" emotional experiences.

Negative emotions were uncommon, but reports of "sadness" were also linked to "touching" and "moving" experiences—and to a participant categorizing a work as art. "Even the thrills from a haunted house are ultimately experienced as positive, as we experience our hearts racing while we know we are safe," says study lead author Lauri Nummenmaa, a researcher at the University of Turku in Finland. "Art likely exploits similar mechanisms for making us feel good. It activates our autonomic nervous system, and in the peace and quiet of an art gallery this increased bodily activity feels good to us."

The researchers also found the strength of both bodily sensations and emotion was highest for artworks depicting people, dovetailing with the theory that seeing others' actions may trigger sensorimotor mirroring effects. Although the study used only subjective reports and didn't measure objective physiological changes in the body, the data suggest that art perception is an interoceptive process: it involves awareness of the body's internal state. Art may "get under our skin" to shift perception.

"Some forms of art may help subtly shift attention to our bodies, depending on the artistic scene or subject, even to specific regions like the chest or heart," says neuroscientist Jennifer MacCormack, who leads University of Virginia's Affect & Interoception Lab. This could then influence how much we incorporate the body into our emotional experience, she adds. Previous research has linked aesthetic perception of art to the brain's insular cortex, which mediates interoception. Art may be in the whole body—not just the eye—of the beholder. *—Saga Briggs*

ANIMAL BEHAVIOR

Why We Spin

Primates may play with reality by twirling around

Young mountain gorilla hangs on a vine.

In 2011 Marcus Perlman saw a YouTube video of a gorilla named Zola spinning in circles while playing in a water puddle at the Calgary Zoo in Alberta, Canada. In 2017 he noticed Zola again, this time in a viral video from the Dallas Zoo in Texas. Zola whirled in a blue plastic kiddie pool as the water splashed up around him.

Perlman, a lecturer in English language and linguistics at the University of Birmingham in England, had researched communicative gesturing, and the videos sparked his curiosity about this form of great ape behavior. He went on to find around 400 more clips of spinning apes. "They spin pirouettes on their feet; they do backflips; they roll on their side; they do somersaults forward; they roll down hills, spin on ropes," Perlman says.

Adriano Lameira, a primatologist and evolutionary psychologist at England's University of Warwick, was also fascinated by online videos of apes spinning. He and Perlman co-authored a paper in *Primates* that focuses on rope twirls. In the films they analyzed, orangutans, gorillas, chimpanzees and bonobos hung by their hands from ropes or vines and turned through the air at dizzying speeds.

At first glance, such spinning might look like a stereotypy: repetitive movement that some animals engage in when bored. But to Lameira, the apparent playfulness made it seem instead like an enriching and creative activity. The apes seemed to lose themselves in their movements. They would let go of the rope and topple over from unsteadiness—and then get up and spin again and again.

Cat Hobaiter, a primatologist at the University of St. Andrews in Scotland, who wasn't involved in the study, says she has encountered plenty of spinning in wild chimpanzees and gorillas. "It's one of their favorite kinds of play when they're young," she says. Gorillas in particular "literally spin themselves until they kind of drop and fall over from dizziness," Hobaiter adds.

In their paper, Lameira and Perlman document the spinning and speculate about what that drive to spin means in our closest animal relatives. Spinning turns the world into a blur for apes—including humans. The movement disrupts humans' vestibular system, which senses changes in motion, orientation, position and body speed. We might feel dizzy or light-headed, get a head rush, and act elated or giggly. Perhaps for this reason, spinning is a staple of children's play. Human children indulge in spinner bowls at playgrounds and flock to merry-go-rounds and carnival rides that spin them through the air. For many autistic people, spinning serves as self-stimulation. In some orders of Sufism, a branch of Islam, dervishes spin in a form of religious dancing that induces a spiritual and trancelike state. "Spinning is proactively tapped for rapture," Lameira and Perlman write in their study.

The speed of the apes' rope spinning was comparable to that of pirouettes in professional ballet, the turning of Ukrainian hopak dancers, Sufi dervishes and suspended spinning-rope acts by circus artists. The apes spun at 1.43 revolutions per second on average, and the fastest speed they reached was 3.3 turns per second. These are speeds that can induce physiological "highs" in humans.

Humans seek out altered mental states to lose their senses of self and time, says Marc Wittmann, a psychologist at the Institute for Frontier Areas of Psychology and Mental Health in Germany and author of the 2018 book *Altered States of Consciousness: Experiences Out of Time and Self*. "When we are present-oriented, without past and future rumination, we feel much better."

But Perlman says it's a big jump to imagine gorillas experiencing a psychedelic or spiritual experience, even if we share physiology suggestive of similar physical effects. The world probably keeps spinning around these primates when they finally come to a stop, Hobaiter says—but we don't know whether they enjoy and seek out that feeling.

And as Annika Paukner, a comparative psychologist at Nottingham Trent University in England, notes, "even if spinning leads to altered mental states in humans, that doesn't mean that apes will experience the same kind of altered mental states." Dogs, horses and some birds also spin, she points out, and by focusing only on great apes, we could be missing other explanations for this behavior.

The researchers say their next steps could evaluate whether spinning is more common in gorillas compared with other apes and investigate twirling preferences by sex or age. They are also intrigued by the origins of spinning. "I can imagine this being sort of elaborated over millennia and over the course of human evolution," Perlman says. "That basic drive to seek altered perception and altered mental states could be common to our primate cousins." Many primate species eat fermented foods, and it's possible they get a bit soused, researchers have documented.

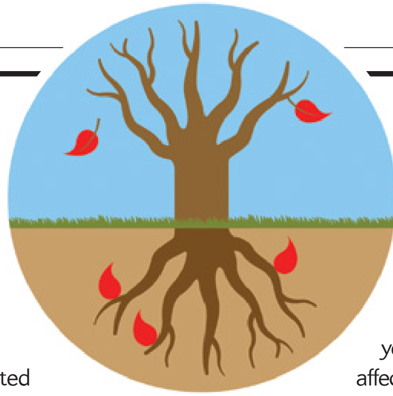
Both spinning and consuming fermented fruit relate to larger questions about how animals amuse themselves and what their pastimes might say about what it's like to be a gorilla or a chimp. Seeing apes spin raises the possibility that nonhuman primates might indulge in the delight of manipulating their normal perceptual states, similarly to humans who change consciousness through drugs or physical activities. "It highlights the subjectivity of experience," Perlman says, "and it opens up that maybe there are different perspectives on reality—not that they are necessarily thinking deeply about this difference." —*Shayla Love*

Ibrahim Suha Derbent/Getty Images

ECOLOGY

Zombie Fires

An unexpected culprit keeps wildfires alive belowground



Some wildfires just won't die—even though they're buried. Although temperatures and shortening days limit wildfire activity at the end of the Northern Hemisphere's summer, "zombie" fires can smolder underground all winter and reemerge in spring. In what investigators say is the first field study to examine how this phenomenon works and its ecological impacts, they found that the stealthy flames draw nourishment from a surprising subterranean source.

A satellite-based study published in 2021 revealed that zombie or "overwinter" fires are becoming more common in Arctic forests, probably because of climate change. It also demonstrated that sites of overwinter fires in Alaska and northern Canada could be identified via visual clues in satellite images (the locations were later confirmed by firefighters on the ground). For the new research, biologist Jennifer Baltzer of Canada's Wilfrid Laurier University and her colleagues used these data to choose nine overwinter sites for a closer look at the soil and vegetation involved.

Their results, presented at the General Assembly of the European Geosciences Union in April, were a surprise. Contrary to the hypothesis that overwinter fires sustain themselves in carbon-rich, organic soil layers known as peat, the researchers learned that most of them had burned in drier, upland sites with dense tree populations; the find suggested fires had instead smoldered underground in woody tree roots. "This is not what we were expecting," Baltzer says.

The discovery means carbon emissions from these underground fires may be lower than previously thought, and they may also have less of an effect on soil health and plant regeneration. Additionally, because these fires did not reach the forest canopy—instead felling trees by burning their roots—less plant material overall combusted than in many single-season fires the team visited.

"In terms of emissions and ecological impact," Baltzer says, "it may be a relatively good-news story."

Still, researchers don't yet know how zombie fires affect global emissions. "If it burns underground in part of a tree, it's not releasing ancient carbon," says Thomas Smith, who studies environmental geography at the London School of Economics and Political Science and was not involved in the study. But he notes that peat fires burning long-buried carbon do, worryingly, exist elsewhere, including Siberia. There, smoke rising from the snow in winter has evoked concern about peat-driven zombie fires.

The hot, dry conditions that lead to big wildfire seasons also support overwinter fires. And such fires may themselves be part of a positive-feedback cycle, reigniting to create even more fires in the next year. Closely examining more sites will help scientists determine what conditions support zombie fires, supporting efforts toward more reliable detection and effective firefighting, the researchers say. *—Rachel Berkowitz*

COGNITION

Seeing Numbers

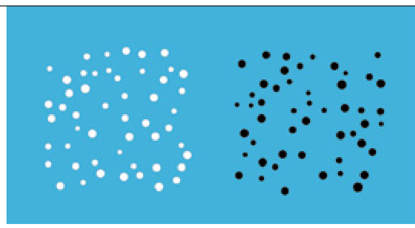
Where is the line between knowing and guessing?

At a quick glance, could you tell the difference between a group of 20 dots and a group of 30? What about 20 and 21? It seems like there must be a point at which you'd simply be guessing, but recent research suggests otherwise.

Given enough opportunities, people consistently perform better than chance on this kind of task even when the numerical difference is extremely small, according to a study published in the *Journal of Numerical Cognition*.

"It's a very simple question with a really interesting answer," says University of Pennsylvania psychologist Sami Yousif, who was not involved in the study. "I love very elegant, very simple results like this."

The research team showed more than 400 participants pairs of dot groups for just one second. On easy practice trials such as 30 versus 20 dots, participants chose the larger group correctly almost every time. For 20 versus 21 dots, they were right nearly 60 percent of the time. And even in the hardest comparison—50 versus 51 dots—participants consistently answered correctly on 51.3 percent of trials. It's a small but statistically significant difference, the researchers say.



Which has 50 dots, and which has 51?

"If you are asked to make a judgment about which of two groups contains more stuff, and you have a little bit of intuitive feeling that one of them is more than the other, you should trust your gut," says study lead author Emily M. Sanford, a cognitive scientist now at the University of California, Berkeley.

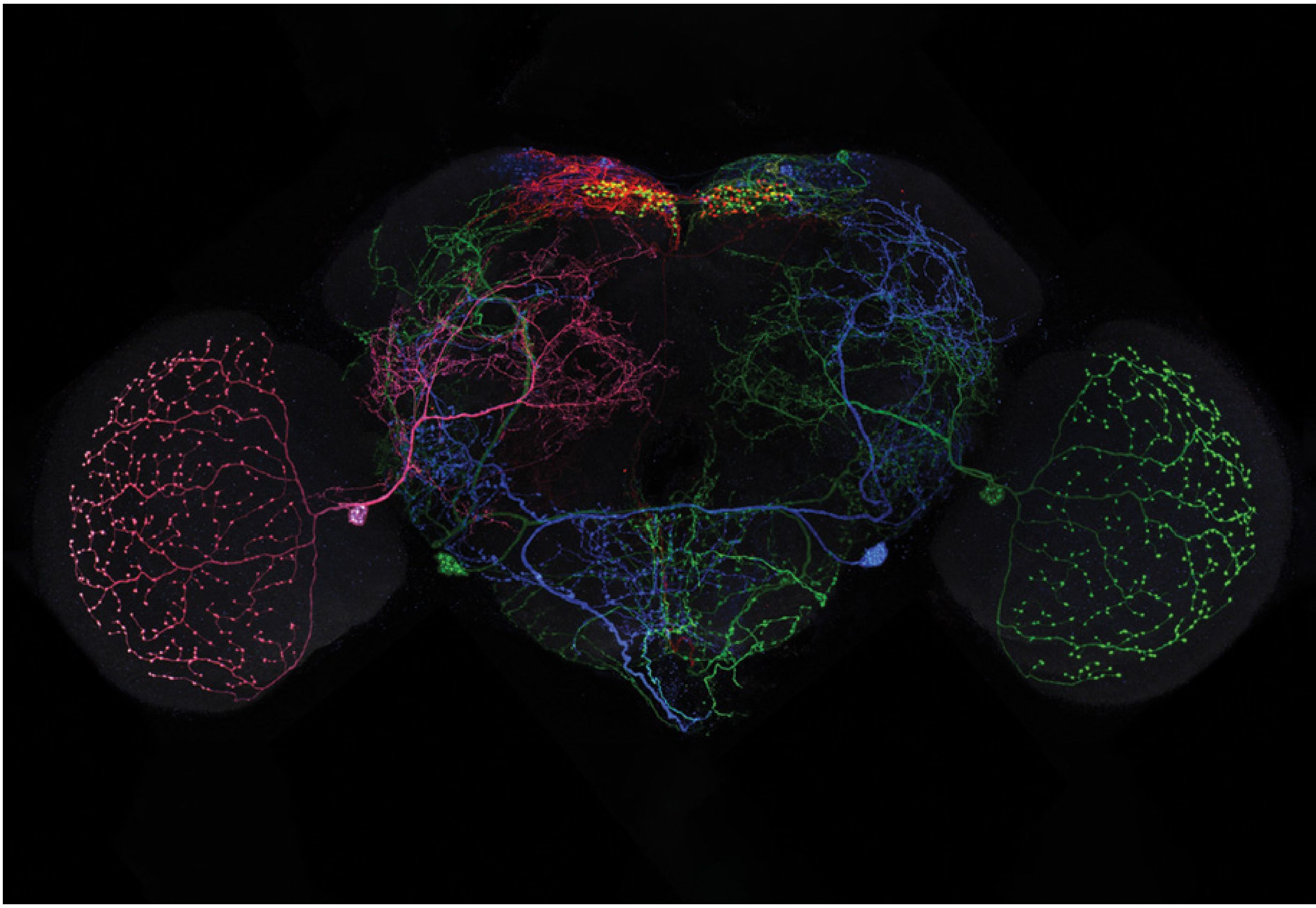
The researchers tested two mathematical frameworks for thinking about this situation: one with a hard limit on the fine numerical differences people can perceive and one without. They found their data fit better with the limitless model, suggesting that even with numbers as high as 100 versus 101, the task would become harder but not impossible.

The implications go far beyond number sense, Sanford says, because the study builds on a theory describing perception across many different stimuli: the work suggests that when deciding which of two circles has a larger area, for example, a person wouldn't be truly guessing unless the circles were exactly the same size.

This theory predicts that with enough trials, an individual will perform above chance on even the hardest perceptual tasks. But there is intuitive appeal, even among some scientists in the field, to the idea that humans have a perceptual limit. "We can't tell that 51 is greater than 50, so we sort of forget that the perceptual system is doing that," Yousif says. "I see it as a landmark paper in the sense that it really lays bare some of the assumptions that have, in my opinion, plagued this literature for a while." *—Nora Bradford*

Emily M. Sanford/University of California, Berkeley

Illustration by Thomas Fuchs



NEUROSCIENCE

Science in Images

By Jordan Kinard

Everybody wants to get inside a fruit fly's head. These insects' simple brains are invaluable to neuroscientists studying information processing and task management, and a new, unprecedentedly detailed map of fruit fly brain connections now makes that easier. After years of work on their FlyLight initiative, researchers at the Howard Hughes Medical Institute in New York have compiled photographs of more than 74,000 fruit fly brains—detailed down to the individual neuron—from flies in over 5,000 genetically modified lineages. This image shows one such fly brain, with brain lobes and individual activated neurons clearly visible.

The more detailed a brain connection map (called a connectome) is, the better it helps scientists understand how nervous systems work. "The brain is a giant neural circuit," says Geoffrey Meissner, a Howard Hughes researcher and lead author of the new mapping study in *eLife*. If you want to know how the brain works, he says, "you have to know the map of the circuit."

But even in a 200,000-neuron fly brain—compared with a human's 86 billion to 120 billion neurons—it can be difficult to get images of single brain cells and their shapes. Lewis & Clark College biologist Tamily Weissman-Unni, whose work focuses on cataloging brain circuits, notes that a neuron's individual shape holds key information about the kinds of input it receives and the role it plays. Likening this to examining a freeway system, she says, "We know where the big, huge pathways are, but your question might be about what an individual car does on that freeway."

For decades scientists have mapped neurons by observing fruit flies with inserted genes that produce a yeast protein called Gal4 when neurons carry out certain processes. Gal4 activates another added gene that can produce pigment proteins visible by microscope—letting researchers see what brain parts are involved when the organism does anything from flying to tasting food. Unfortunately, it's hard to discern individual cells when a slew of neurons activate at once.

The FlyLight researchers developed a method they named MultiColor FlpOut, in which various inserted pigment-producing genes interact with an enzyme called Flp to label activated neurons with different colors and levels of pigmentation. Scientists then assembled these samples like a puzzle to map the respective chains of individual cells that activate during certain activities—and to build their impressive new database.

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

Geoffrey Meissner/FlyLight

QUANTUM PHYSICS

Reverse Freeze

Quantum fluid freezes when heated

To melt a solid, heat it. To freeze a liquid, cool it. It's simple—except when it isn't, because quantum mechanics can flip even the intuitive logic of melting and freezing on its head.

Physicists recently showed in *Nature Communications* how heating a quantum fluid—in this case, a very cold gas of magnetic atoms—can actually "freeze" it into an orderly state called a supersolid. This unexpected behavior was first observed in 2021, but scientists couldn't explain it until now.

"This paper manages to introduce some new theoretical description, which now successfully describes experimental observations people didn't understand before," says physicist Tim Langen of the University of Stuttgart, who was not involved in the new study.

Quantum particles, which are both particles and waves, can be imagined as clouds of probability. The odds of finding a particle at any point in the cloud at a given moment are linked to the particle's wave behavior, described by a formula called a wave function. In a quantum fluid, particles smear together into a single entity whose collective behavior is governed by just one wave function. Typically they are also "superfluids"—they flow without friction.

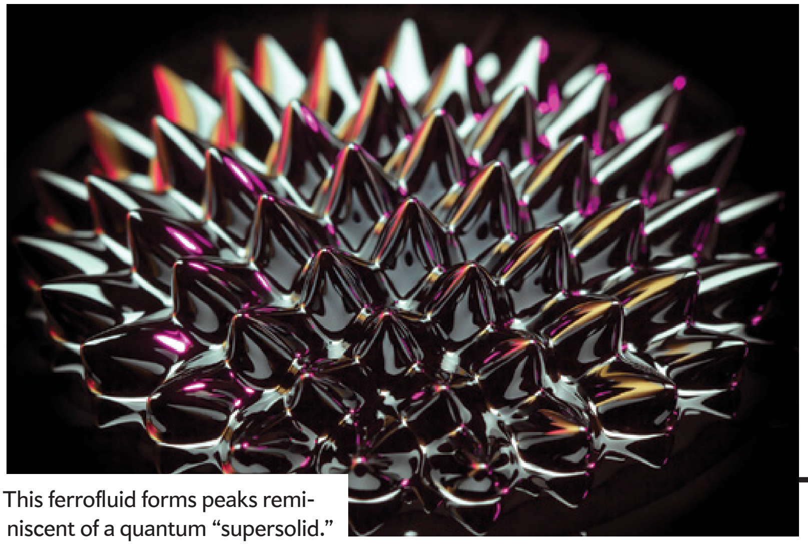
Supersolids have similar properties, but they additionally have orderly, rippled structures, says study co-author Francesca Ferlaino, an experimental physicist at the University of Innsbruck and the Institute for Quantum Optics and Quantum Information, both in Austria.

In 2021 Ferlaino and her team found that warming an ultracool quantum fluid of the magnetic rare earth element dysprosium could solidify it into a supersolid's distinctive peaks. But given such an unexpected result, "we had to convince ourselves with the theory that this is actually something that makes sense," says study co-author Thomas Pohl of Denmark's Aarhus University.

The team now shows that this counterintuitive behavior arises from a strange synergy between heat and the natural tendency of magnetic atoms to pile up.

At the atomic level, temperature is motion: it measures the energy of particles' random movements. Heating something is thus a bit like shaking it, injecting random thermal fluctuations that in this case nudge atoms out of the quantum fluid's unified, blurred-together state. Because they're so magnetic, these breakaway particles interact strongly with the quantum fluid and encourage dysprosium atoms' inherent inclination to stack. This influence changes the entire quantum fluid's wave function, pushing it into a supersolid state with regularly spaced peaks.

"How weird and counterintuitive this is—this is what I like finding as a physicist," says study co-author Juan Sánchez-Baena of the Polytechnic University of Catalonia and Aarhus University. "If you find all the things that you are expected to find, things get boring." —*Elise Cutts*



Oliver Hoffmann/Alamy Stock Photo

This ferrofluid forms peaks reminiscent of a quantum "supersolid."

NEWS AROUND THE WORLD

Quick Hits

By Allison Parshall

AUSTRALIA

Officially the last known Tasmanian tiger, or thylacine, died in 1936, but the species' potential survival has become an urban legend. By analyzing 271 reported sightings deemed relatively credible, researchers found the marsupial might have lasted decades longer than previously thought—but is probably indeed extinct today.

BRAZIL

The endangered frog *Xenohyla truncata* may be the first known amphibian pollinator. Most frogs are carnivores, but after finding plant matter in *X. truncata*'s guts, researchers observed the frogs slurping nectar from milk fruit trees before hopping off covered in pollen.

CANADA

A Manhattan-size mass of driftwood floating in the Mackenzie River stores 3.1 million metric tons of carbon, new research shows. Arctic conditions can preserve such buildups of dead trees for centuries, but this process may be disrupted as permafrost thaws.

CHAD

A trail camera revealed the first lion seen in 20 years in Chad's Sena Oura National Park. Poaching has wiped out lion populations, but this lioness was healthy and in her prime, raising hope for the species' survival in the region.

FRENCH POLYNESIA

Conservationists released 5,000 *Partula* tree snails on the islands of Tahiti and Moorea, the largest release to date of an "extinct in the wild" species. The snails, which keep the forest healthy by eating decaying plants and fungi, were originally displaced by human introduction of predator species.

PACIFIC OCEAN

Coastal animals such as jellyfish and sponges are surviving and reproducing on plastic trash in the northern Pacific Ocean's Great Pacific Garbage Patch, thousands of miles from shore, researchers found. They worry the floating debris could carry these organisms to new shores as invasive species.

UGANDA

As climate change threatens two of the world's most popular coffee varieties, a native Ugandan type known as excelsa may offer an alternative. The trees take longer to mature but are more heat-resistant, and farmers are now exporting the aromatic beans to the world.

For more details, visit www.ScientificAmerican.com/jul2023/advances

The Southern Lights at –50° Fahrenheit

—a zeitgeber

When winds were bearable, we sought bliss,
sat, admired the aurora australis
as an escape from our blackest abyss.

We gazed up into rarefied air, clear

and pristine in every echelon,
an atmospheric phenomenon,
solar wind collisions of protons

and electrons high in the exosphere.

Who needs Parthenon or Birth of Venus
when blue lights swirl low, pink coronas kiss
clouds, neon greens arc, deep reds stripe across
stars. We invoke healing through kinesis.

Paul Brooke is a professor of English at Grand View University in Des Moines, Iowa. His five books of poetry include *Sirens and Seriemas* (Brambleby, 2015). As a former biologist and naturalist, he co-authored *Jaguars of the Northern Pantanal:* Panthera onca *at the Meeting of the Waters* (Academic Press, 2020).

Lake Vostok

—a zeitgeber

Frantic call sent us to the Pole of Cold.
We maneuvered slowly, sought a controlled
approach through shifting drifts in our Hägglund.

At camp, they drilled to 4,000 meters

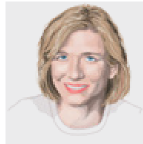
to contact a subglacial lake and wrangle
accretion ice and microbe samples,
millions and millions of years old, fragile.

After, we warmed ourselves near space heaters.

We could be on Europa, on untold
frozen moons; sort unique species; unfold
the quilt of the cosmos; piece blocks; hold
no bias; embrace the raw edge, uncontrolled.

Author's Note: The rhyme scheme for this form that I invented (based on the term "zeitgeber," meaning an external cue that affects the way the body is regulated by circadian rhythms or time cycles) is aaabcccbaaaa and represents three months with sun above the horizon, one month of twilight, three months of darkness, one month of twilight, and four months of sun above the horizon.

James Stone/Alamy Stock Photo



Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American.* She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

Cancer and Our Body Clock

Disrupting circadian rhythms is tied to cancer. Bolstering them might prevent it

By Lydia Denworth

I usually get up by 7 A.M. and am in bed by 10 P.M. I tend to eat meals at the same times of day, too. This may sound a little dull, but it's essential for my productivity. It's also a schedule that rarely disrupts my body clock. And a steady clock, it turns out, just might help me and many other people avoid cancer and some other diseases, according to new research.

What I call a body clock really means circadian rhythms, from the Latin for "about" and "day." These are the body's internal biological pacemakers, physiological fluctuations that help us adjust to the phases of a 24-hour day by synchronizing with environmental cues such as light, dark, temperature and food intake. These rhythms affect sleeping and waking, feeding and fasting, endocrine cycles, immune function, and cell growth.

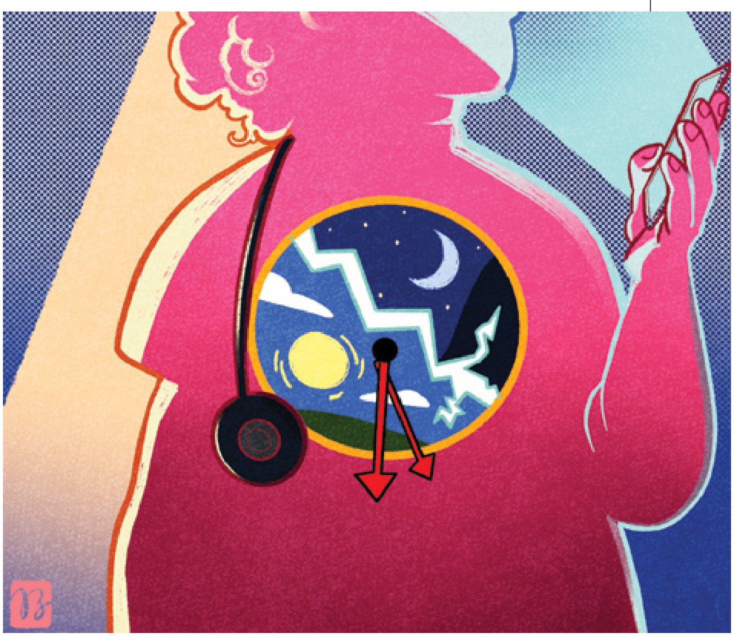
For some time now epidemiological studies of night-shift workers have linked disruptions in circadian rhythms to cancer and other diseases. Much of the evidence concerned breast cancer and to a lesser extent prostate cancer. Duration of shift work made a difference—nurses who worked night shifts for up to 30 years were at moderately increased risk for breast cancer compared with those who did shorter stints, and those who worked such shifts for more than 30 years had the highest risk. In 2019 the World Health Organization reaffirmed and updated a research statement from the agency showing that shift work is a probable carcinogen.

Now there is even more evidence involving other types of malignancies, including liver, lung and colorectal cancers, from a spate of new studies. "We're starting to understand the reasons these things happen," says Selma Masri, a circadian biologist at the University of California, Irvine, who has shown how circadian disruption pushes colon cancer progression by interfering with the way certain genes are expressed.

The cancer connection comes about through several mechanisms. Circadian disruption affects metabolic pathways, the chemical reactions that produce energy in the body. It tampers with immune function. It also compromises the fidelity of DNA repair in cells. Adult human cells divide every 18 to 24 hours, and one function of the circadian clock is to tell cells to do that at night to avoid DNA damage from sunlight. "When the clock gets disrupted, cells don't know when to divide," says circadian biologist Satchidananda Panda of the Salk Institute for Biological Studies. "They can divide faster and become a tumor."

Circadian disruption doesn't only occur in shift workers. It happens when we consistently don't get a good night's sleep—scientists say this can mean waking up for two or three hours between 10 P.M. and 5 A.M. at least once a week. Wakeful episodes can be caused by jet lag, staying out late, or looking at blue-light-emitting phone screens—which mimic daylight—at night. When and what we eat also cues our rhythms, just as light and dark do, so add snacking at midnight to the list of things to avoid.

The growing understanding of circadian rhythms also could offer help through what's known as chronotherapy. Certain chemotherapy treatments, for example, are more effective when given in accordance with a patient's rhythms. Now researchers are exploring differences in the timing of radiation therapy. Drugs that bolster natural rhythms are also under investigation.

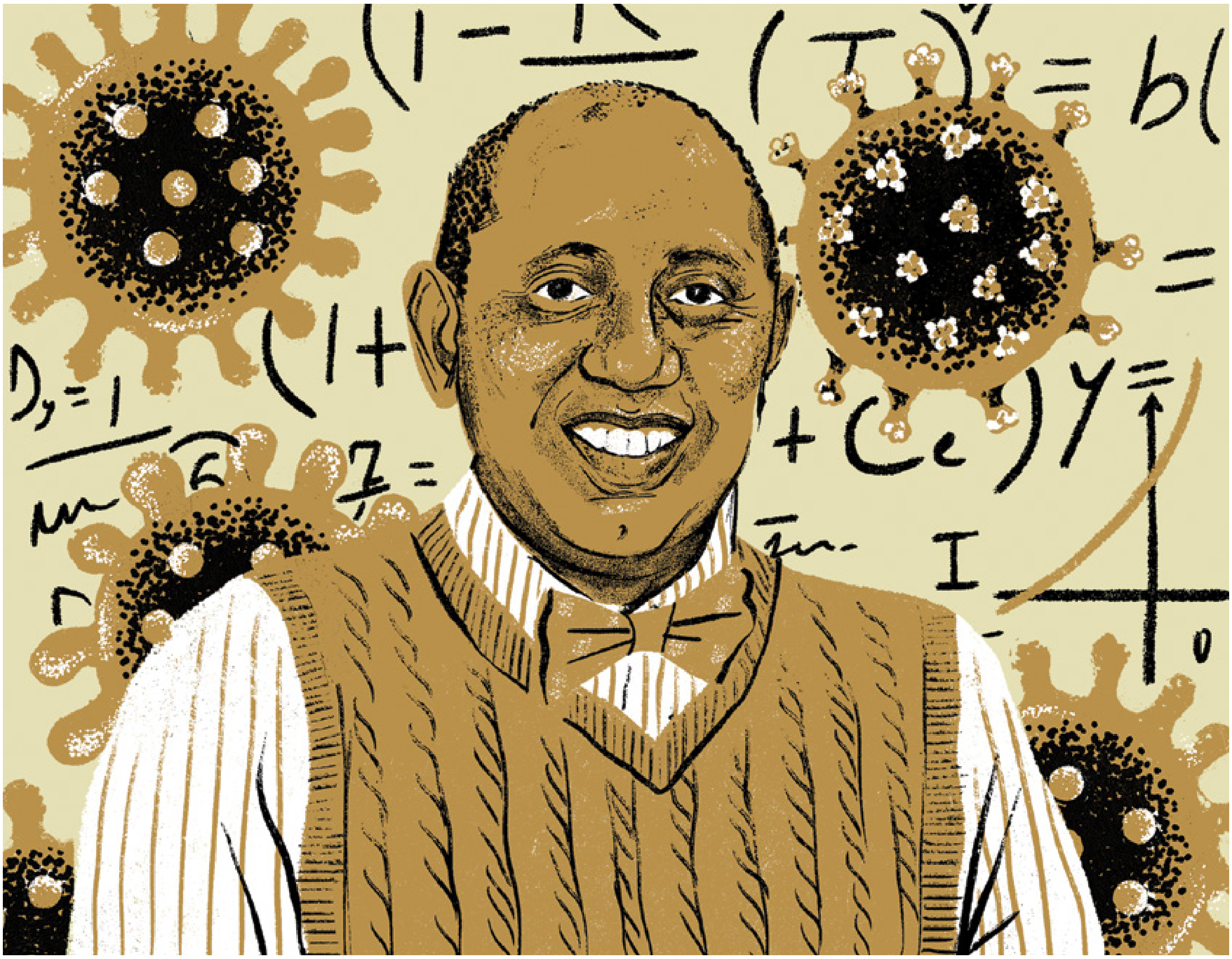


Shift work is critical and not going away, says Katja Lamia, a circadian biologist at Scripps Research, but there might be ways of reducing its toll on the body. Her research suggests that subtle increases in body temperature might be an important factor in circadian disruption. If that turns out to be right, Lamia says, "we can use noninvasive monitoring of body temperature in shift workers to evaluate who's at risk and take a personalized scheduling approach."

For those who don't work at night, changing some routines might be enough. A good night's sleep should be a priority. Eating habits can also play a role. Panda and his colleagues are investigating a practice known as time restricted eating (TRE) or intermittent fasting. That might mean delaying breakfast by an hour or two until cortisol levels drop and eating dinner at least three hours before your habitual bedtime. In a 12-week study of firefighters, TRE benefited their metabolic health and improved their sleep. In mice, it has been shown to reduce the risk of cancer or to slow the growth of tumors.

Maybe, Panda says, respecting our circadian rhythms can help protect our time-sensitive bodies. SA

Illustration by Jay Bendt



How Mathematics Can Predict—and Help Prevent—the Next Pandemic

Mathematician Abba Gumel uses calculations and models to prepare for future disease outbreaks

By Rachel Crowell

Predicting and understanding disease outbreaks doesn't just involve epidemiology. It takes math, too. For centuries mathematicians have tackled questions related to epidemics and pandemics, along with potential responses to them. For instance, 18th-century Swiss mathematician Daniel Bernoulli is credited with developing the first mathematical epidemiology model, which focused on analyzing the effects of smallpox inoculation on life expectancy. Mathematicians have continued this work to the present day, including during the COVID pandemic.

One such researcher is Abba Gumel, a mathematician and mathematical biologist at the University of Maryland, College Park. He was recently elected to the current class of fellows of the American Association for the Advancement of Science (AAAS). Mathematicians such as him are indispensable to the mission of identifying and averting the next pandemic. Succeeding in this quest, however, requires that they unite with experts from other fields and work together to solve these multifaceted disease-transmission problems.

Gumel spoke to SCIENTIFIC AMERICAN about how he is using mathematics to combat infectious diseases and about the ques-

Illustration by Irene Rinaldi

Rachel Crowell is a Midwest-based writer covering science and mathematics.

tions he hopes to address before the next pandemic hits.

[*An edited transcript of the interview follows.*]

Tell me about a time that one of your recent findings surprised you.

We showed in our paper on COVID lockdown measures that the number of cases, hospitalizations and mortality would have been dramatically reduced if we had started community lockdowns a week or two earlier than we did. This means hitting the disease hard early, before it enters the exponential phase of transmission. It would have dramatically altered the course of the pandemic in the U.S. and perhaps saved hundreds of thousands of lives.

What role can mathematicians play in preventing the next pandemic?

What mathematicians are doing to help prevent the next one is basically working on lessons we have learned. We have learned that masks worked from mathematical analysis and modeling but also from what happened in society. Societies that have high coverage of masks and high-quality masks did well in reducing cases and mortality. Vaccines work, we have shown clearly, if we raise the level of herd immunity required. For the next pandemic, if we have certain vaccines with starting efficacies, we can predict the minimum proportion we need to vaccinate to achieve vaccine-induced herd immunity.

We're coming up with this bucket list of things to do to prevent, we hope, the next one but even if we do get hit—and we're going to get hit—to minimize the burden of the next one and to greatly suppress it before it becomes a problem. These are things we need to do to make sure the next one doesn't kill one million Americans.

Sometimes when I talk about it, I cry because I see that if we had done the right thing, none of this would have happened.

What are some pressing open questions you hope to address before the next pandemic hits?

I am interested in determining whether stockpiling high-quality face masks and making them widely available early in a new COVID-like pandemic can obviate the need to shut down the economy until a safe and effective vaccine becomes available.

I am interested in determining the impact of increases in global temperature caused by global warming on the population and distribution of wild animal populations and associated viral zoonotic diseases and the likelihood of a spillover event.

I am also interested in quantifying the burden of a potential highly contagious and highly fatal pandemic of a contact-based disease such as Ebola viral disease. The world community thankfully averted such a catastrophe when we came together and effectively contained the Ebola outbreaks that took place in Guinea, Liberia and Sierra Leone in 2014–2016.

> **"Sometimes when I talk about it, I cry because I see that if we had done the right thing, none of this would have happened."** —*Abba Gumel*

Before the COVID pandemic, you mainly focused on mosquito-borne diseases. Are there fundamental differences in how you approach studying infectious diseases such as malaria that involve a vector?

Yes, there's a big difference. There's no direct human-to-human transmission. Mosquitoes get infected by biting infectious humans. If I'm infected and a mosquito takes a blood meal from me, there's some probability that the mosquito can also get my *Plasmodium* parasite and become infected. So the modeling types are different.

West Nile is transmitted by mosquitoes not only to humans but also to other hosts such as crows. But the birds fly long distances, so we use spatial models.

What are some other factors that affect your modeling decisions?

The type of model you choose depends on the level of data you have. An agent-based model allows you to track each individual: their risk of getting infected, what they do each day, and all that. That's very useful in determining who infected whom. But it's data-hungry. You need a lot of data at an individual level.

The type of model you choose depends on the problem you want to solve, the type of data you have and the quality of the data.

What does your selection as an AAAS Fellow mean to you?

It's a huge honor. And the honor belongs to the large number of people in my support network.

This gives me an additional platform to multiply my efforts in community outreach. I've been focused on Africa and other developing regions of the world to provide opportunities for people to be the best they can become in STEM [science, technology, engineering and mathematics]. I'm focused on young people, especially women. I'm focused on getting a lot more women in rural areas to get into STEM and be among the best. I'm very worried about gender inequity. I'm doing whatever I can to bridge that gap. Particularly, where I came from in Africa [Nigeria], we need a lot more women in STEM.

We have a tremendous responsibility. We need to make science accessible to everyone around the world. It doesn't work at all if only a few countries are scientifically advanced. Look at what's happened. COVID started in China, but it became a problem for everyone.

We're all vulnerable to what's happening in faraway places—the same with inequity in STEM, inequity in health care, inequity in economics. If we're doing well, but our neighbor is not, it's just a matter of time before we also suffer. It's the same thing with viral things happening in faraway places. We had better pay attention because it's a plane ride away from coming to us. SA

ANIMAL BEHAVIOR

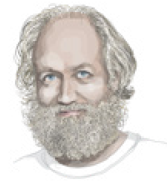
Bees and other insects are far more cognitively complex than previously thought—a revelation that has wide-ranging ethical implications

By Lars Chittka

Photographs by Levon Biss

THE INNER LIVES OF INSECTS

Lars Chittka is a professor of sensory and behavioral ecology at Queen Mary University of London. His latest book is *The Mind of a Bee* (Princeton University Press, 2022).



IN THE EARLY 1990S, WHEN I WAS A PH.D. STUDENT AT THE FREE UNIVERSITY of Berlin modeling the evolution of bee color perception, I asked a botany professor for some advice about flower pigments. I wanted to know the degrees of freedom that flowers have in producing colors to signal to bees. He replied, rather furiously, that he was not going to engage in a discussion with me, because I worked in a neurobiological laboratory where invasive procedures on live honeybees were performed. The professor was convinced that insects had the capacity to feel pain. I remember walking out of the botanist's office shaking my head, thinking the man had lost his mind.

Back then, my views were in line with the mainstream. Pain is a conscious experience, and many scholars then thought that consciousness is unique to humans. But these days, after decades of researching the perception and intelligence of bees, I am wondering if the Berlin botany professor might have been right.

Researchers have since shown that bees and some other insects are capable of intelligent behavior that no one thought possible when I was a student. Bees, for example, can count, grasp concepts of sameness and difference, learn complex tasks by observing others, and know their own individual body dimensions, a capacity associated with consciousness in humans. They also appear to experience both pleasure and pain. In other words, it now looks like at least some species of insects—and maybe all of them—are sentient.

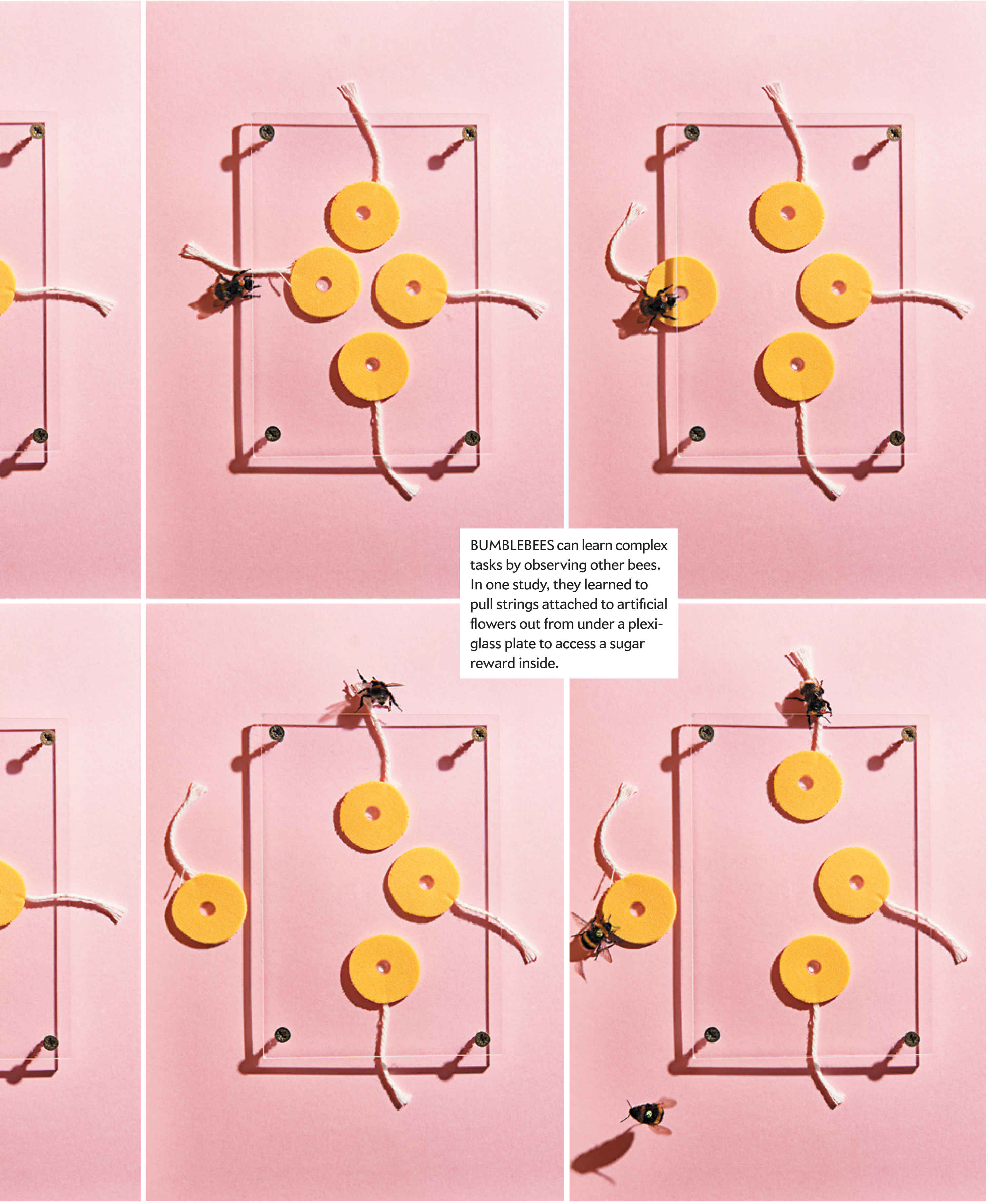
These discoveries raise fascinating questions about the origins of complex cognition. They also have far-reaching ethical implications for how we should treat insects in the laboratory and in the wild.

SIGNS OF INTELLIGENCE

THE CONVENTIONAL WISDOM about insects has been that they are automatons—unthinking, unfeeling creatures whose behavior is entirely hardwired. But in the 1990s researchers began making startling discoveries about insect minds. It's not just the bees. Some species of wasps recognize their nest mates' faces and acquire impressive social skills. For example, they can infer the fighting strengths of other wasps relative to their own just by watching other wasps fight among themselves. Ants rescue nest mates buried under rubble, digging away only over trapped (and thus invisible) body parts, inferring the body dimension from those parts that are visible above the surface. Flies immersed in virtual reality display attention and awareness of the passing of time. Locusts can visually estimate rung distances when walking on a ladder and then plan their step width accordingly (even when the target is hidden from sight after the movement is initiated).

Given the substantial work on the sophistication of insect cognition, it might seem surprising that it took scientists so long to ask whether, if some insects are that smart, perhaps they could also be sentient, capable of feeling. Indeed, the question had been on my mind for decades. Since the early 2000s I have used it in debates for undergraduate student group tutorials. I viewed it as a thought-provoking intellectual exercise, but the discussions invariably ended with the conclusion that the question is formally unanswerable. We have no direct window into the inner world of an animal that cannot verbally communicate its thoughts and feelings—which is to say, all nonhuman animals. The question of whether insects are sentient remained academic.

I began to think the issue had real-life relevance when, 15 years ago, Thomas Ings, now at



BUMBLEBEES can learn complex tasks by observing other bees. In one study, they learned to pull strings attached to artificial flowers out from under a plexiglass plate to access a sugar reward inside.

Anglia Ruskin University in England, and I performed an experiment in which we asked whether bumblebees could learn about predation threat. Certain spider species called crab spiders perch on flowers to catch pollinating insects, including bees. We built a plastic spider model with a mechanism that would briefly trap a bumblebee between two sponges before releasing it. The bumblebees showed a significant change in their behavior after being attacked by the robotic spider. Perhaps unsurprisingly, they learned to avoid spider-infested flowers and meticulously scanned every flower before landing. Curiously, however, they sometimes even fled from imaginary threats, scanning and then abandoning a perfectly safe, spider-free flower. This false-alarm behavior resembled symptoms of post-traumatic stress disorder in humans. Although this incidental observation did not constitute formal evidence of an emotionlike state, it did move the possibility of such states in insects into the realm of possibility.

Other research hinted that insects might also have positive states of mind. Many plants contain bitter substances such as nicotine and caffeine to deter herbivores, but these substances are also found in low concentrations in some floral nectars. Researchers wondered whether pollinators might be deterred by such nectars, but they discovered the opposite. Bees actively seek out drugs such as nicotine and caffeine when given the choice and even self-medicate with nicotine when sick. Male fruit flies stressed by being deprived of mating opportunities prefer food containing alcohol (naturally present in fermenting fruit), and bees even show withdrawal symptoms when weaned off an alcohol-rich diet.

Why would insects consume mind-altering substances if there isn't a mind to alter? But these suggestive hints of negative and positive mind states still fell short of what was needed to demonstrate that insects are sentient.

PLEASURE AND PAIN

I BEGAN TO CONSIDER how one might more directly test emotionlike states in insects. So-called cognitive bias tests have been developed to evaluate the psychological welfare of animals such as rats that live in captivity. These tests are essentially versions of the proverbial glass that can be half-full or half-empty: optimistic humans might view the ambiguous glass as nearly full, whereas pessimists would judge the same glass as being nearly empty. My collaborators and I decided to develop a similar test for bees.

We trained one group of bees to associate the color blue with a sugary reward and green with no reward, and another group of bees to make the opposite association. We then presented the bees with a turquoise color, a shade intermediate between blue and green. A lucky subset of bees received a surprise sugar treat right before seeing the turquoise color; the other bees did not. The bees' response to the ambiguous stimulus depended on whether they received a treat before the test: those that got the pretest sugar approached the intermediate color faster than those that didn't.

The results indicate that when the bees were surprised with a reward, they experienced an optimistic state of mind. This state, which was found to be related to the neurotransmitter dopamine, made the bees more upbeat, if you will, about ambiguous stimuli—they approached it as they would the blue or green colors they were trained to associate with a reward. It also made them more resilient toward aversive stimuli, as occurs in humans: bees that were given a surprise dose of sugar recovered faster when ambushed by a fake predator, taking less time to reinitiate foraging than their peers that did not receive sugar before the simulated attack.

Other work suggests that bees can experience not only optimism but also joy. Some years ago we trained bumblebees to roll tiny balls to a goal area to obtain a nectar reward—a form of object manipulation equivalent to human usage of a coin in a vending machine. In the course of these experiments, we noticed that some bees rolled the balls around even when no sugar reward was being offered. We suspected that this might be a form of play behavior.

Recently we confirmed this hunch experimentally. We connected a bumblebee colony to an arena equipped with mobile balls on one side, immobile balls on the other, and an unobstructed path through the middle that led to a feeding station containing freely available sugar solution and pollen. Bees went out of their way to return again and again to a "play area" where they rolled the mobile balls in all directions and often for extended periods without a sugar reward, even though plenty of food was provided nearby. There seemed to be something inherently enjoyable in the activity itself. In line with what other researchers have observed in vertebrate creatures at play, young bees engaged more often with the balls than older ones. And males played more than females (male bumblebees don't work for the colony and therefore have a lot more time on their hands). These experiments are not merely cute—they provide further evidence of positive emotionlike states in bees.

All this research raised the more uncomfortable question of whether bees might also be capable of experiencing pain. Investigating this issue experimentally presents researchers with a moral dilemma: if results are positive, the research might lead to improved welfare of trillions of wild and managed insects. But it would also involve potential suffering for those animals that are tested to obtain the evidence. We decided to do an experiment with only moderately unpleasant stimuli, not injurious ones—and one in which bees could freely choose whether to experience these stimuli.

We gave bees a choice between two types of artificial flowers. Some were heated to 55 degrees Celsius (lower than your cup of coffee but still hot), and others were not. We varied the rewards given for visiting the flowers. Bees clearly avoided the heat when rewards for both flower types were equal. On its own, such a reaction could be interpreted as resulting from a simple reflex, without an "ouch-like" experience. But a hallmark of pain in humans is that it is not just an automatic, reflexlike response. Instead one may opt to grit one's teeth and bear the discomfort—for example, if a reward is at stake. It turns out that bees have just this kind of flexibility. When the rewards at the heated flowers were high, the bees chose to land on them. Apparently it was worth their while to endure the discomfort. They did not have to rely on concurrent stimuli to make this trade-off. Even when heat and reward were removed from the flowers, bees judged the advantages and disadvantages of each flower type from memory and were thus able to make comparisons of the options in their minds.

This finding alone is not a decisive proof that bees experience pain, but it is consistent with that notion, and it is only one of several indicators. Bees and other insects also form long-term memories about the conditions under which they were hurt. And they have specialized sensors that detect tissue damage and are connected to brain regions that also process and store other sensory stimuli. These creatures have the necessary neural equipment to modulate pain experiences by top-down control. That is, they are not constrained by simple reflex loops when responding to noxious stimuli but display the flexibility to modify their responses according to current circumstances, in the same way as we can choose to press a hot door handle to escape a burning building.

Critics could argue that each of the behaviors described earlier could also be programmed into a nonconscious robot. But nature cannot afford to generate beings that just pretend to be sentient. Although there is still no universally accepted, single experimental proof for pain experiences in any animal, common sense dictates that as we accumulate ever more pieces of evidence that insects can feel, the probability that they are indeed sentient increases. For example, if a dog with an injured paw whimpers, licks the wound, limps, lowers pressure on the paw while walking, learns to avoid the place where the injury happened and seeks out analgesics when offered, we have reasonable grounds to assume that the dog is indeed experiencing something unpleasant.

Using a similar logic, my colleagues and I reviewed hundreds of studies from the literature across several orders of insects to search for evidence of a capacity to feel pain. Our analysis revealed at least reasonably strong evidence for this capacity in a number of taxa, including cockroaches and fruit flies. Crucially we also found no evidence that any species convincingly failed any criterion for pain-like experiences. It appears that in many cases, scientists simply haven't looked thoroughly enough for indications that the insect species they study experience discomfort.

AN ETHICAL OBLIGATION

IF AT LEAST SOME INSECTS are sentient and can feel pain, as appears to be the case, what are the implications of that revelation? I sometimes get asked questions along the lines of "Does this mean that I can't kill a mosquito that lands on my arm, even though it might infect me with a life-threatening disease?" No, it does not mean that. The insight that many conventional livestock animals are probably sentient hasn't stopped humans from killing them. But it has resulted in an awareness (and legislation in many countries) that this should be done in such a way as to minimize distress and pain. If death is instantaneous, such as when you slap the mosquito on your skin, there is little room for suffering. Setting ants alight with a magnifying glass, as children are sometimes taught to do for fun, is a different matter.

A QUEEN BUMBLEBEE and workers tend a nest. Open wax structures are honey or pollen pots; closed structures contain larvae.

The treatment of insects in scientific laboratories also deserves consideration. Insects transmit some of the deadliest human diseases, so research into how they can be controlled is obviously important. In addition, we could develop remedies for a variety of human health disorders by studying their molecular genetic and neurobiological underpinnings in insects such as fruit flies. Researchers are often encouraged by funding agencies to work on insects rather than vertebrates in part because there are supposedly no ethics to consider. But some of the methods used to study them have the potential to cause intense distress. Insects are sometimes embedded in hot wax after their extremities are removed, their head capsules are then opened and electrodes inserted into various parts of their brain—all done without anesthesia.

Scientists with whom I have discussed the topic have sometimes countered that we still haven't delivered irrefutable proof that insects can suffer. This is factually accurate, but given what we now know about the plausibility of pain experiences in some insects, wouldn't we instead want to be reasonably certain that specific invasive treatments do *not* cause suffering? We urgently need more research into this question and into the identification and development of suitable anesthetics.

Some of my colleagues are worried about the introduction of vertebrate-style legislation and paperwork for work on insects. I understand their concern. Politics has a way of turning well-intentioned recommendations from scientists into bureaucratic nightmares, which can hobble scientific progress while bringing about no appreciable benefits for animal welfare. A potentially more valuable approach would be if insect researchers themselves took the lead in considering how to minimize suffering, to reduce numbers of insects tested or sacrificed when possible, and to ensure that the severity of procedures is proportional to knowledge gain in both curiosity-motivated and applied research.

Insects are used on a far grander scale in the feed-and-food industry. More than a trillion crickets, black soldier flies, mealworms and other species are killed annually, and the sector is expanding rapidly. Often touted as a replacement for some or all the vertebrate meat in people's diets, insect farming is considered an environmentally friendly alternative to the conventional farming of livestock such as cattle or chickens. Another perceived advantage of insect farming is that there are supposedly no ethical concerns with insects like there are with cows and chicken. In fact, some insect-farming companies specifically promote the notion that insects lack any capacity for pain.

This claim is demonstrably incorrect for all insect species tested so far. Science tells us that the methods used to kill farmed insects—including baking, boiling and microwaving—have the potential to cause intense suffering. And it's not like they're being sacrificed for a great cause. The bulk of the industry does not actually seek to replace human consumption of vertebrate meat with insects. Instead most of the slaughtered insects go to feeding other animals that are farmed for human consumption, such as salmon or chicken. In other words, farmed insects are being used to turbocharge, not replace, the conventional livestock production.

But even if replacing vertebrate meat was the goal, we need scientific evidence for what constitutes humane slaughtering methods and ethically defensible rearing conditions for insects. It is possible that such evidence will reveal less capacity for suffering in some larval stages of some species, but until we have that evidence, we should err on the side of caution.

Unfortunately, a vegetarian or vegan diet is not necessarily free of ethical concerns for the welfare of insects either. Many insects share our taste for the leaves, roots, vegetables and fruits of the plants that we consume. As a result, several million metric tons of pesticides are deployed every year worldwide to streamline the production of cheap food for maximum profit. These pesticides poison and kill countless insects (and many other animals), often by slow processes lasting several days.

The plant-eating insects are not the only ones affected. The adverse effects of the insecticides known as neonicotinoids on bees are well documented. Although their concentration in flower nectar and pollen is typically too low to kill instantly, these insecticides affect learning, navigation, foraging efficiency and reproductive success, severely impacting populations of wild bees. This collateral damage to bees is viewed as concerning because these are beneficial insects with an important utility for us humans: they pollinate our crops and garden flowers. But these pesticides also have the potential to cause mass suffering in bees and other insects—another reason to ban, or at least strongly limit, their use.

Bees in particular face additional stress from commercial pollination operations. Mass production of raspberries, blueberries, apples, tomatoes, melons, avocados and many other kinds of produce is dependent on honeybees or bumblebees being commercially mass-reared, bred, farmed and shipped to distant locations to pollinate the crops.

Almond milk, a popular alternative to dairy milk, relies to a large extent on the California almond bloom, one of the biggest commercial pollination events in the world. Migratory beekeepers load more than half of North America's honeybees (several dozen billion individuals) on trucks to be shipped to 800,000 acres of almond tree monoculture in California during the flowering period, then ship the bees back to their original locations or other crop-flowering events.

The "colony collapse disorder" that you may have heard about in the media is not just the result of some well-known pathogens but also of honeybees being literally stressed to death by ruthless beekeeping practices. Even brief shaking of bees induces a pessimistic emotionlike state. Now imagine the effects of intense and prolonged vibrations imposed on bees when they are trucked across continents in sealed hives, sustained on artificial food and unable to defecate outside the hive, then typically finding themselves in crop monocultures that lack the diversity of floral food bees normally require. Scientists have extensively studied the detrimental effects of stress on the immune system in several species, including insects. For invertebrate creatures such as insects, researchers have generally assumed the stress is strictly physiological, like a plant wilting when deprived of water. The possibility that in insects stress is at least partly psychological in nature deserves further exploration.

To live, to eat, we almost inevitably kill other living things, even if our labor division means that you personally don't do the killing. But to the extent that the affected creatures are probably sentient, we have a moral obligation to minimize their suffering—whether in research labs, on feed-and-food farms, or in agricultural settings.

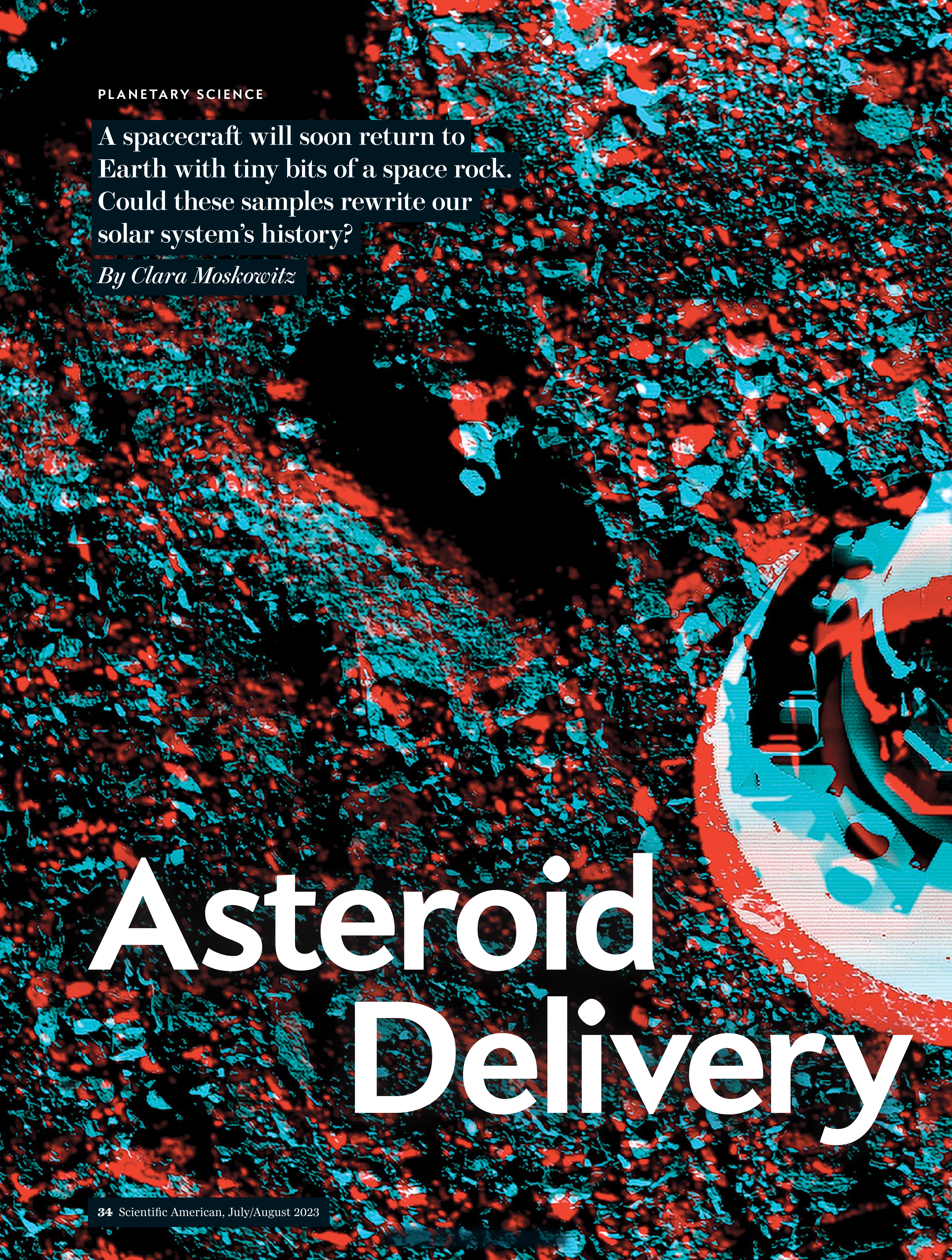
The fact that to date there is no smoking-gun type of proof for any animal's sentience does not mean we're off the hook. On the contrary, the reasonably strong psychological, pharmacological, neurobiological and hormonal indicators of sentience that we now have for many animals, including some insects, mean that acquiring evidence in the opposite direction is in order. We should demand reasonably strong evidence of the absence of sentience before subjecting them to interventions that have the potential to cause intense distress. SA

FROM OUR ARCHIVES

The Mind-Boggling Math of Migratory Beekeeping. Ferris Jabr; ScientificAmerican.com, September 1, 2013.

scientificamerican.com/magazine/sa

BEE JOY: In another experiment, bees chose to roll balls around rather than visiting feeding stations—a form of play.



PLANETARY SCIENCE

Asteroid Delivery

A spacecraft will soon return to Earth with tiny bits of a space rock. Could these samples rewrite our solar system's history?

By Clara Moskowitz

OSIRIS-REX'S SAMPLING ARM reaches toward the asteroid Bennu in this anaglyph double image.

Clara Moskowitz is a senior editor at *Scientific American*, where she covers space and physics.

WHAT WOULD IT BE LIKE TO HOLD A PIECE OF OUTER SPACE IN YOUR HAND? Some lucky scientists will find out soon when NASA's OSIRIS-REx spacecraft (shorthand for Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) returns from its seven-year mission. The probe will drop off a canister holding about a cup of pebbles and dust from the surface of the near-Earth asteroid Bennu. "Bennu is a time capsule of the early solar system, and we're cracking it open," says Amy Hofmann, an isotope geochemist at NASA's Jet Propulsion Laboratory, who is a co-investigator on the mission. "We get to be the first people to see what's in there. I'm getting goose bumps talking about this."

Hofmann is one of around 200 scientists who will receive portions of the cargo OSIRIS-REx brings back. On September 24 the probe is set to release its sample return capsule, which will barrel through Earth's atmosphere and make a parachute landing at the Department of Defense's Utah Test and Training Range. If all goes well, recovery teams will helicopter it to a portable clean room to remove its heat shield and back shell and then fly it to a specially prepared facility at the Johnson Space Center in Houston. Scientists there will carefully open the inner container, handling it inside a glove box to keep out all contaminants, to retrieve some of the only pristine primordial bits of asteroid ever to reach Earth's surface. (Meteorites are great, too, but their unprotected burn through our atmosphere alters them.)

The samples will reveal the state of the solar system when it was first forming, including which amino acids and other chemical compounds important for biology were present. "The 'O' in 'OSIRIS-REx' is really for the origin of life," says Dante S. Lauretta of the University of Arizona, the mission's principal investigator. "We want to understand the role that these carbon-rich asteroids played in delivering the precursors of life to Earth."

OSIRIS-REx launched in 2016 and arrived at Bennu in 2018. It spent two years near the space rock, making measurements with its onboard cameras, spectrometers, and other instruments. Those scans revealed a lot about Bennu, including that it's more like a pile of loosely bound rubble than a solid object and that it holds water-bearing minerals. But the real payoff will be the samples. "We have access to the absolute state-of-the-art technology here on Earth," says co-investigator Michelle Thompson, a planetary scientist at Purdue University. "Having time, having this huge team and the ability to do coordinated analyses, to look at the same sample with multiple different techniques—there's really nothing that can replace that. Sample return is a cornerstone of planetary science."

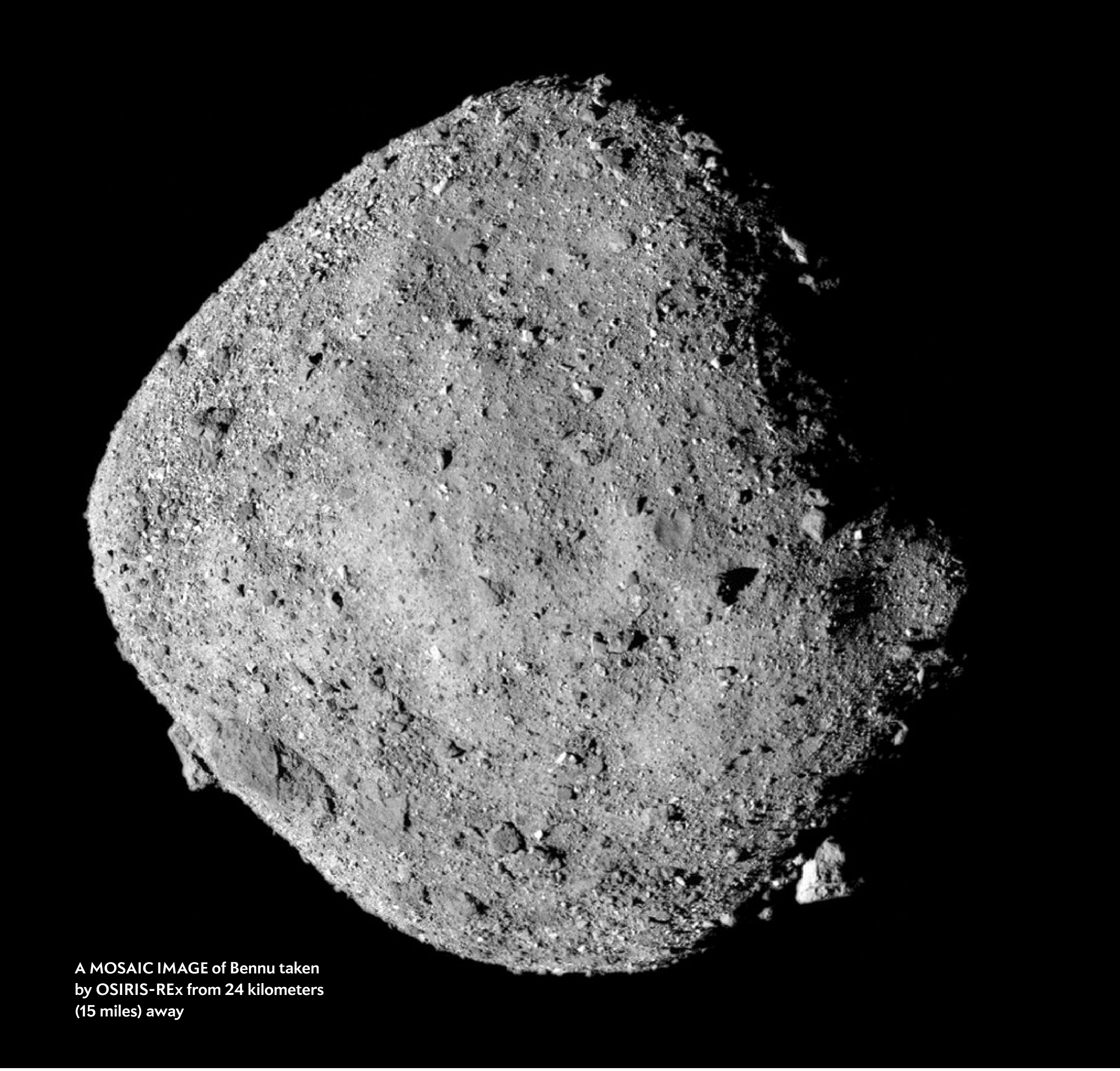
In October 2020 the spacecraft made a close approach to the asteroid, briefly touching the surface with its Touch-and-Go Sample Acquisition Mechanism (TAGSAM), a robotic arm that fired a burst of nitrogen gas to stir up dust and rock, which it then funneled into its collector head. "It looks like an air filter, except we brought the air," Lauretta says. Photographs taken during the collection process suggest the mission scooped up plenty of material. Some extra bits of sample even got stuck to the outside of the TAGSAM.

After scientists open up the TAGSAM back on Earth, a quarter of its haul will go to the OSIRIS-REx team, who will disperse it from the Johnson Space Center to laboratories around the world. Four percent of the sample will go to Canada, a contributor to the mission, and at least 0.5 percent will be sent to Japan, which carried out the two Hayabusa missions that brought back the world's first asteroid samples in 2010 and 2020. But 70 percent of the stuff returned will remain untouched by anyone, at least for now. "Just like with Apollo, we want to preserve the vast majority of the samples for future scientists," says University of Arizona planetary scientist Andrew Ryan, leader of the OSIRIS-REx Sample Physical and Thermal Analysis Working Group. "We'll have new questions, there will be future tools, and we want to make sure we haven't burned through the whole sample."

Even the first scientific findings should significantly expand our knowledge of asteroids like Bennu. Ryan's team will measure how much heat the material conducts, how much space there is between particles in each grain, and how strong the force is that holds the pieces together. Comparing their findings with estimates researchers made when the spacecraft was orbiting Bennu will help them better characterize other asteroids from remote measurements—a potentially crucial ability if we need to deflect an Earth-bound rock in the future.

Hofmann will use a special kind of mass spectrometer called an Orbitrap to identify specific organic molecules with different isotopic compositions within her samples and compare their

NASA/Goddard/University of Arizona (*preceding pages and opposite page*)



A MOSAIC IMAGE of Bennu taken by OSIRIS-REx from 24 kilometers (15 miles) away

amounts. Measuring the extent to which multiple carbon 13 atoms (a rare, stable form of carbon with an extra neutron) replace carbon 12 (the most common form of carbon) in a particular molecule, for instance, can tell researchers about the temperature when the compound formed. “These measurements weren’t even possible when OSIRIS-REx was first proposed,” Hofmann says. “It’s forensics for planetary science.”

Thompson will use electron microscopes to study how Bennu has been weathered over time by impacts from other space rocks and by energetic particles streaming off the sun. These measurements, combined with the findings of other experiments planned for the samples, aim to provide a comprehensive picture of the state of our early solar system and how it became what it is today. “The questions we’re going to answer are extremely diverse,” she says. “[They cover] everything from understanding and characterizing the building blocks of the solar system to looking at the physical characteristics of the material. We are going to come out of this mission with a totally revolutionized understanding of these types of bodies. Everyone should be very excited.”

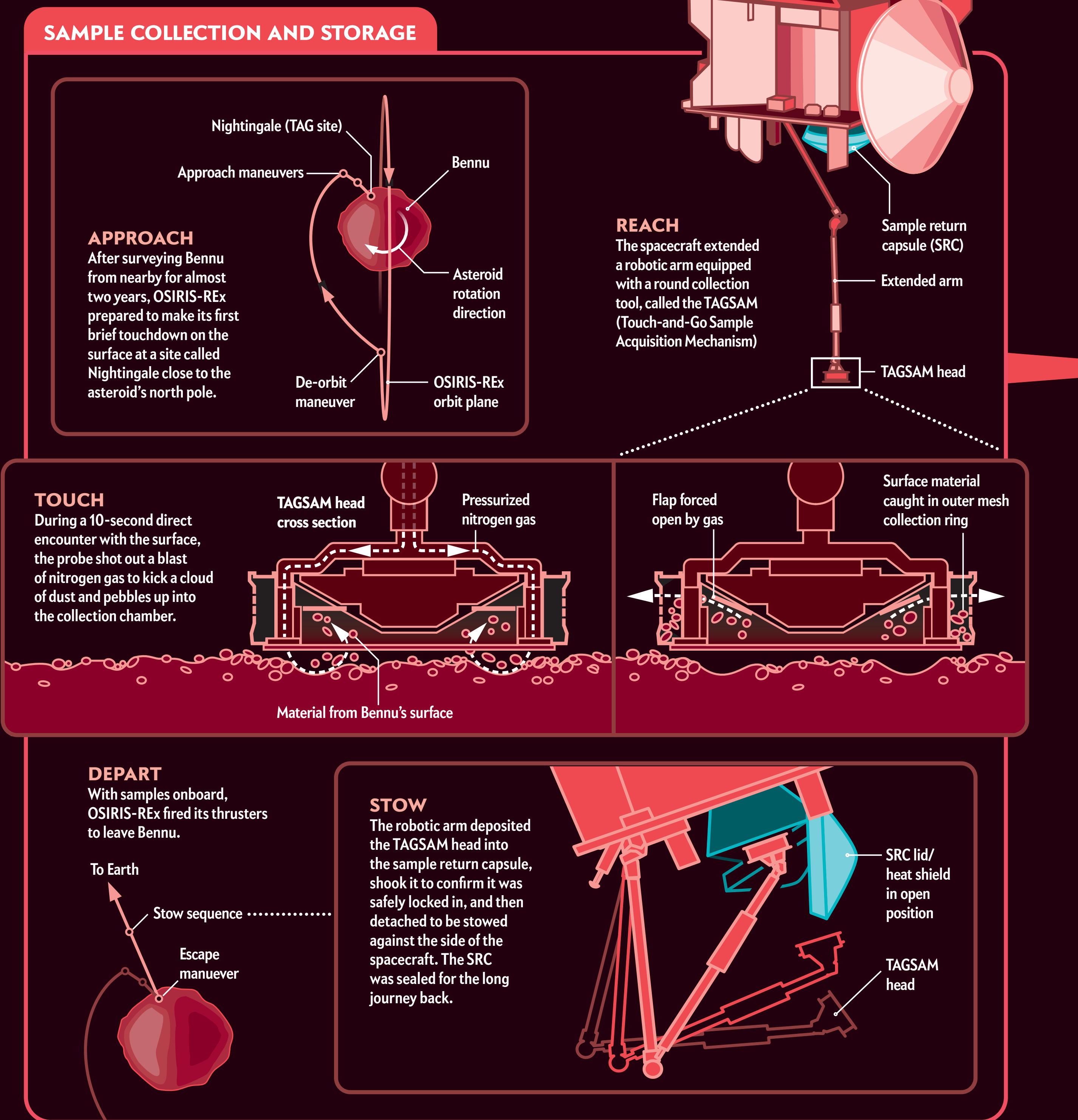
FROM OUR ARCHIVES

The Seven-Year Mission to Fetch 60 Grams of Asteroid. Dante S. Lauretta; August 2016.

scientificamerican.com/magazine/sa

Bringing Bennu Back

The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) spacecraft is preparing for a complicated maneuver to deliver tiny pieces of the asteroid Bennu to scientists waiting back on Earth. The probe briefly touched down on the space rock in 2020 to collect the samples and will drop them off for a parachute landing on September 24.



Graphic by Jen Christiansen

MISSION TIME LINE

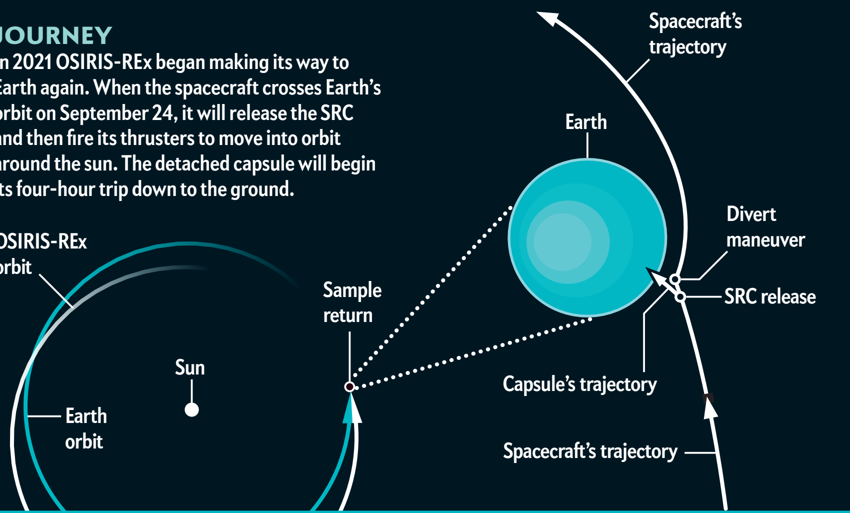
OSIRIS-REx's long-haul mission won't end when it drops off its samples. The probe will travel next to the near-Earth asteroid Apophis, where it will arrive in 2029.

- **2016** — Sept. 8: Launch
- **2017** — Sept. 22: Earth flyby
- **2018** — Dec. 3: Asteroid Bennu arrival
- **2019** — Orbits, surveys, and rehearsals
- **2020** — Oct. 20: Successful Bennu sample collection
- **2021** — Apr. 7: OSIRIS-REx completed its last flyover of Bennu; May 10: Journey back to Earth began
- **2022**
- **2023** — Sept. 24: Sample capsule expected to be delivered to Earth
- **2024**
- **2025**
- **2026**
- **2027**
- **2028**
- **2029** — Asteroid Apophis arrival

SAMPLE RETURN

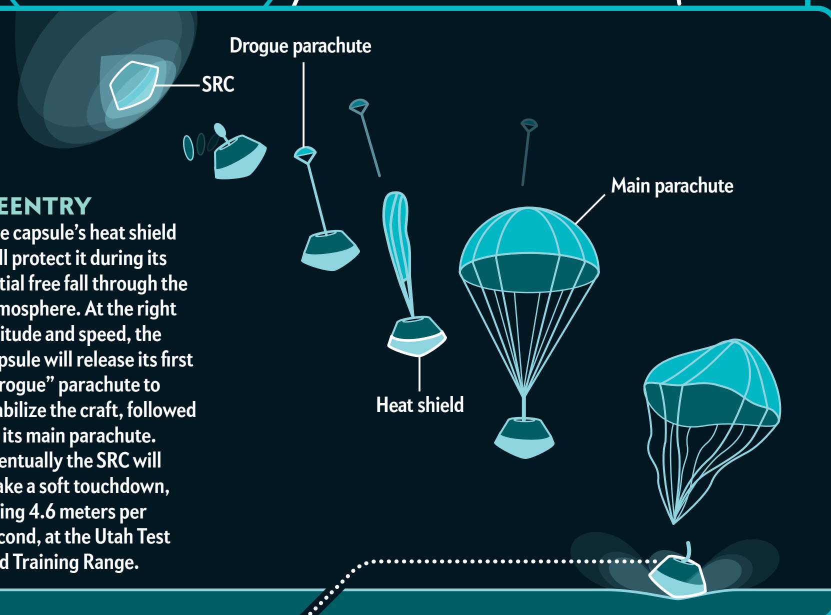
JOURNEY

In 2021 OSIRIS-REx began making its way to Earth again. When the spacecraft crosses Earth's orbit on September 24, it will release the SRC and then fire its thrusters to move into orbit around the sun. The detached capsule will begin its four-hour trip down to the ground.



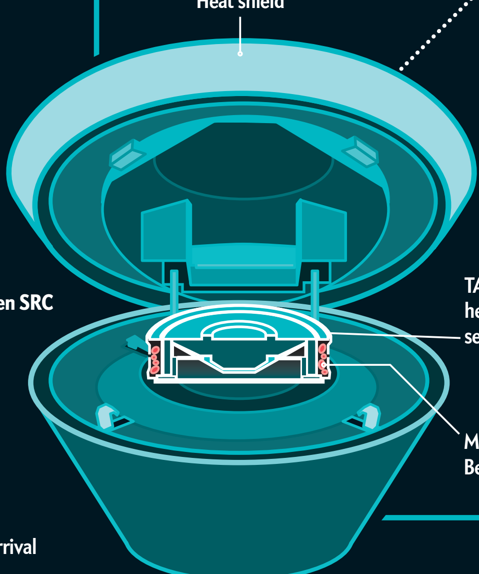
REENTRY

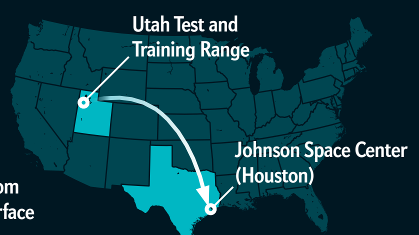
The capsule's heat shield will protect it during its initial free fall through the atmosphere. At the right altitude and speed, the capsule will release its first "drogue" parachute to stabilize the craft, followed by its main parachute. Eventually the SRC will make a soft touchdown, going 4.6 meters per second, at the Utah Test and Training Range.



RETRIEVAL

A helicopter team will fly out to retrieve the SRC and take it to a portable clean room nearby. There technicians will remove the SRC's heat shield and back shell to reveal the sample canister and TAGSAM head inside. Within 24 hours all these pieces will be flown to Houston, where scientists will open the canister to retrieve their treasure in a specially prepared clean room at the Johnson Space Center.





Sources: "OSIRIS-REx, Returning the Asteroid Sample," by Thomas M. Ajluni et al. IEEE Aerospace Conference Paper, March 2015; and "OSIRIS-REx: Sample Return from Asteroid (101955) Bennu," by Dante S. Lauretta et al., in *Space Science Reviews*, Vol. 212; August 2017 (*primary references*)

ECOLOGY

Parrot In

vasions

These smart, social birds are thriving in cities around the world

By Ryan F. Mandelbaum

Photographs by Ali Cherkis

MONK PARAKEETS nest atop the entryway to Green-Wood Cemetery in Brooklyn, N.Y.

Ryan F. Mandelbaum is a science writer and birder based in Brooklyn, N.Y.

AT BROOKLYN'S GREEN-WOOD CEMETERY THE LIVING GET AS MUCH attention as the dead. Groundskeepers maintain the 478-acre historic landmark as an arboretum and habitat for more than 200 breeding and migratory bird species. But many visiting wildlife lovers aren't interested in those native birds. They're at the entryway, their binoculars trained on the spire atop its Gothic Revival arches. They've come to see the parrots.

The urban cemetery hosts dozens of long-tailed, dove-size parrots, lime green with gray accents on their foreheads and chests, called Monk Parakeets. (Parrots and parakeets are part of the same family.) These birds maintain barrel-size stick nests not just at this cemetery but across the city. They live in nearby Connecticut, too. Monk Parakeets and other species of parrots are in Chicago, Miami, Tampa, New Orleans, Los Angeles, Houston, Dallas, San Antonio and Austin. Red-masked Parakeets live on Telegraph Hill in San Francisco. Rosy-faced Lovebirds decorate the palm trees of Phoenix. Parrots are present in all of Mexico's 10 largest cities, as well as Barcelona, Amsterdam, Brussels, Rome and Athens. They're in Tel Aviv. And Singapore. All around the world, parrots are taking over with a resounding *SQUAWK!!!*

Today at least 60 of the world's 380 or so parrot species have a breeding population in a country outside their natural geographical range. Each successful transplant has its own story: some are benign, others a threat to the local wildlife; some are abundant in their home ranges, whereas others rely on cities as a refuge from extinction. All are by-products of the pet trade and animal trafficking around the world. Because they're parrots, they're smart, adaptable, creative and loud. "They're animals that are really social, and they live in cognitively complex social environments," says Grace Smith-Vidaurre, a postdoctoral fellow at the Rockefeller University and the University of Cincinnati, who studies the birds. "They're like humans in a lot of ways."

The Brooklyn parrots' story begins in South America. When Smith-Vidaurre started her research on the origins and behavior of Monk Parakeets, she thought it was important to visit the birds in their native range, which extends across parts of central South America, including Argentina and Uruguay. She asked the scientist who sponsored her visit whether it would be a challenge to find the birds. No, he said; he could hear them outside his window—they're as common there as pigeons. They live in cities, feed on agricultural crops and in gardens, and nest in exotic trees and power lines.

It's not always clear what makes a specific parrot species successful in habitats beyond their native ranges, Smith-Vidaurre explains. But you can get an idea of it with the Monk Parakeets. As early as 1839, Charles Darwin described this species as a major agricultural pest in South America. "These parrots always live in flocks, and commit great ravages on the corn-

NATIVE to South America, Monk Parakeets have made themselves at home in a number of U.S. cities.

fields," he wrote in his journal. "I was told that near Colonia [del Sacramento, Uruguay,] 2500 were killed in the course of one year."

Monk Parakeets are one of the only parrot species whose members build colonies of stick nests—elaborate, multichambered structures that they maintain cooperatively. These nests allow them to survive in temperate regions of South America, where temperatures regularly drop below 50 or even 40 degrees Fahrenheit on cold winter days—and in New York City with its even colder temperatures.

The Uruguayan government still considers the bird a serious crop pest, and the country's authorities carry out regular culling. Uruguay also has been a top exporter of the bird for the pet trade over the past 50 years.

The trading of wildlife, including parrots, is highly regulated by local, national and international laws, most notably the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). CITES maintains lists of species whose trade either is forbidden or requires permits, including many parrot species. Monk Parakeets aren't currently listed, but some places, such as the state of California, ban them as pets because of their invasive potential.

Our attraction to parrots has played a key role in their rise to world domination. Humans have traded and moved these birds around for millennia. Alexander the Great kept parrots he brought back from India in the fourth century B.C.E. The Romans, too, kept exotic parrots as pets. In North America, archaeologists have carbon-dated Scarlet Macaw bones found in New Mexico's Chaco Canyon—hundreds of miles northwest of the parrots' Central American range—to the 10th century C.E.

Parrots seem to have started establishing populations outside their native ranges more recently. Research published in the *Journal of Zoology* documents parrots breeding in the U.K. as early as 1855. But it wasn't until the 1960s that demand for pet parrots spiked. As more birds were released by or escaped from their owners, colonies started forming in cities around the world. During that era, importers brought Monk Parakeets from South America into the U.S. by the thousands. The birds were breeding in Illinois by 1968 and on Long Island by 1971. They were even reported to be breeding in North Dakota in the 1970s.

Newspapers and local governments in the U.S. were aware of the agricultural damage the birds were doing in their native ranges and also feared they would introduce diseases, says Ben Naddaff-Hafrey, host of the history podcast *The Last Archive,* which is examining New York City's Monk Parakeets in an episode. Some pushed for the eradication of the parrots, and by 1974 New York State declared the mission accomplished. But more likely, Naddaff-Hafrey says, interest in eradication efforts waned as concerns about economic impacts faded and locals grew fond of the birds.

Lynn M. Stone/Minden Pictures

NORTH AMERICA ONCE HAD ITS OWN PARROT. THE CAROLINA Parakeet, a gregarious green parrot with a yellow head, inhabited much of the eastern U.S. Its range is thought to have extended from Florida and the Atlantic Coast west to Texas and north to Illinois and even New York State—it probably lived in many of the same places the Monk Parakeet is found in today. Like the Monk Parakeets, Carolina Parakeets regularly shared spaces with humans and were occasionally seen as crop pests. But unlike today's urban Monk Parakeets, Carolina Parakeets inhabited wet, old-growth forest. They were declared extinct in 1939, probably done in by a combination of deforestation, competition with invasive species, introduced diseases and hunting. Perhaps the Monk Parakeet is taking up some of the niche vacated by the Carolina Parakeet—but it's also a different bird living in a transformed world, one brimming with opportunities for adaptable species.

Although people may have introduced Monk Parakeets to new locations, the birds themselves have made the most of these novel circumstances. Juan Carlos Senar, who is head of research at the Natural Science Museum of Barcelona, started studying the city's Monk Parakeets out of curiosity. The museum hosted Monk Parakeet research in the 1970s as well, before the birds became worrisome. After all, it's objectively interesting to see displaced parrots adapting

to different environments. Senar observed changes in the birds' behavior, such as how at first they bred during the Northern Hemisphere winter, when it was summer in the Southern Hemisphere, then they changed their breeding timing as they got used to their new environments.

Soon the little green parrots were adding new color to the city's tile work. In 2000 the Catalan government asked whether Senar and his team could undertake a formal census. The researchers found that the birds' population had exploded. They now number in the thousands.

The species' impacts have become clear as its numbers have swelled. In the U.S., Monk Parakeets stick to human habitats, where they aren't directly competing with native wildlife for cavities to nest in like other parrots have to do. But this choice means they sometimes end up in conflict with humans. Often they'll build their nests on utility poles—risking power outages and fires.

In Barcelona, the birds cause more types of damage. One of Senar's studies found that in an agricultural area outside the city, parrots caused a loss of 28 percent of the corn crop, 36 percent of the plum crop and 37 percent of the pear crop, among other fruits and vegetables grown there. They also clip many branches from live trees for their nests and eat food that other, native species rely on.

Senar emphasizes that he loves the species—he enjoys watching them and makes a living studying them. But there's a difference between enjoying a few parakeets and dealing with thousands of them roaming the city. He fears they'll soon harm ecosystems beyond the city limits if their population isn't managed: "They're very clever. If we wait too long, it will be nearly impossible to control them."

ANOTHER, EQUALLY ADORABLE PARROT SPECIES, THE Rose-ringed Parakeet (also known as the Ring-necked Parakeet), illustrates how difficult it can be to control these charismatic birds when they set up shop outside their normal range. Like the Monk Parakeet, this species is successful in its native home ranges in South Asia and sub-Saharan Africa, where it can thrive in human-altered habitats. A popular caged bird since at least Victorian times, the green, pink-beaked, long-tailed parrot started escaping increasingly often in the past few decades; before long the Rose-ringed Parakeet established itself in cities across Eurasia and beyond. But unlike Monk Parakeets, Rose-ringed Parakeets don't build their own nests. They rely on nest cavities, a limited resource for native wildlife—and they aren't afraid to fight for those spaces.

As the species began colonizing cities, scientists organized to understand the birds and their impact.

PARROT SPECIES, including the Yellow-crested Cockatoo (*left*), Sulphur-crested Cockatoo (*center*) and Rose-ringed Parakeet (*right*), are flourishing in urban settings around the world.

Martin Willis/Minden Pictures (*left*); imageBROKER/Ronald Wittek/Getty Images (*right*)

In 2013 the European Cooperation in Science and Technology funded ParrotNet, a five-year project, headquartered at the University of Kent in England, involving a network of scientists across Europe tasked with monitoring parrots and communicating their findings to local governments.

Emiliano Mori, a researcher at the Italian National Research Council and former ParrotNet member, first noticed the birds on a Mediterranean summer holiday and wondered how they were affecting the native biodiversity. He began observing the parrots and the outcomes of their invasion. Soon he found that Rose-rings were taking nest sites from a small owl called the Eurasian Scops Owl in Italy. The species wasn't directly reducing the owls' population, but it was pushing them out of their preferred spots.

Evidence of the negative consequences of Rose-ringed Parakeets' entry into new locales continues to mount. Research has shown that they outcompete birds at feeding stations in the U.K., and they regularly kill competitors such as Blue Tits and black rats. All the while their populations have been ballooning in cities around the world.

"Their presence is not good," Mori says. "We can't tell the complete scope of their impacts, but every time we look, there's something new to be discovered." The researchers continue to find new species affected by the birds, he says.

ParrotNet produced policy briefs that were translated into various European languages. Spain has begun removing parakeets. But culling programs are running up against humans' enduring fascination with these birds.

The parrots' cute factor continues to be a challenge in efforts to control them, says biologist C. Jane Anderson, who specialized in charismatic invasive species while she was an assistant professor at Texas A&M University Kingsville. Anderson studied Rose-ringed Parakeets on the Hawaiian island of Kauai, where the birds threaten local agriculture and native species. She used culled samples to determine when the birds bred and how to tell the difference between juvenile and adult females—they look similar, but removing (and euthanizing) the latter is more important for population control.

Anderson can recall multiple anecdotes of public protest hindering invasive-parrot management. Humans are drawn to animals with babylike features, called "baby schema " in psychology: big eyes, big heads and soft bodies. Culling snakes might not lead to much outcry, but people like parrots.

It's important to remember how the birds arrived in the first place, Anderson says. She doesn't want to demonize the parrots; rather she views controlling them as undoing the damage humans caused. "The truth is humans moved these animals around," she says. "I understand why people would be excited to see a parrot in Barcelona. But they shouldn't be there."

It's also important to understand that our cities

GREEN-WOOD CEMETERY'S Monk Parakeets and other urban parrots are by-products of the pet trade and wildlife trafficking.

are not sterile places devoid of wildlife that needs protection. Cities can be as ecologically valuable as the surrounding countryside—New York City is a major migratory bird hotspot, for example. Perhaps the most worrisome consequence of the Rose-ringed Parakeets is that they outcompete and kill a type of threatened bat called the greater noctule at the site of their largest known colony in Europe—an urban park in the Spanish city of Seville.

THE PARADOXICAL TRUTH OF THE MATTER IS THAT CITIES can also serve as vital habitat for some parrot species. Australian cities host several native parrots, including the Sulphur-crested Cockatoo. This big, white parrot, named for its sleek yellow mohawk, is a regular sight around gardens in Melbourne, Brisbane, Sydney, and beyond. Although their population is in decline overall, they're not listed as threatened, and they have found a way to survive successfully in cities. They've inhabited urban spaces as long as there have been urban spaces, says Lucy Aplin of the Max Planck Institute of Animal Behavior in Radolfzell, Germany, and the Australian National University. "Parrots have the potential, if given the opportunity, to exhibit rapid adaptation to anthropogenic change."

In contrast to Monk and Rose-ringed Parakeets, which start breeding between the ages of one and three years and lay at least three eggs at a time, Sulphur-crested Cockatoos don't generally breed until they're at least three or four years old, and they lay just two to three eggs per nesting season. They're particular about where they nest, seeking out large cavities in old trees. Yet they've been able to thrive in Australia's major metropolitan areas.

Certain traits of Sulphur-crested Cockatoos make them quite well suited to city life. For one thing, they are generalists, feeding on whatever food they can find—fruits, invertebrates or a discarded chicken bone. And they're highly intelligent, social creatures capable of solving problems and teaching their solutions to others. These birds can build a culture around urban living, passing knowledge through social networks like humans do. Aplin studies a behavior that has emerged in Sydney's Sulphur-crested Cockatoos: they've figured out how to open garbage bins. A group of the birds in southern Sydney first learned to open the bins, and they transferred the knowledge to nearby cockatoo roosts. Birds outside the network don't necessarily know how to do it. Aplin's work has shown that birds on opposite sides of the network have diverged into subcultures, opening the bins in different ways.

For some imperiled parrot species, cities may be more than just another comfortable place to call home—they can be a lifeline. Parrots whose native populations are threatened with extinction are holding on in some of the world's largest cities. Consider Hong Kong's Yellow-crested Cockatoos.

During the 1980s and into the 1990s, pet traders exported tens of thousands of Yellow-crested Cockatoos from their native Indonesia to Hong Kong, says Astrid Alex Andersson, a postdoctoral researcher at the University of Hong Kong. Enough birds escaped captivity or were intentionally released by their owners that they founded a colony in the city. Although much of Hong Kong is forested, these birds prefer to nest and feed in the ornamental trees found in the island's urban areas and don't seem to be outcompeting any native species.

About 200 Yellow-crested Cockatoos live in Hong Kong—approximately 10 percent of the bird's remaining population, says Caroline Dingle of the University of Hong Kong. Population decline from poaching pressure in its native habitat led the International Union for Conservation of Nature to designate the species as critically endangered. Andersson is studying whether the species has found a useful refuge in the city, where it's not subject to poaching pressure. "It's possible that these populations, if you do small things to support them in cities, can function as species arks—backup populations for the wild ones," she says.

Nevertheless, city living isn't all great for parrots. There's predation: Mori says feral Rose-ringed Parakeets regularly become prey for raptors, for example. Even for the endangered Yellow-crested Cockatoo, it'll take further work to determine whether the Hong Kong populations can actually function as a genetic reservoir or whether city life has altered them too much to sustain the species. As part of her research, Andersson is investigating how the city cockatoos differ genetically from the native population.

A similar question preoccupies Smith-Vidaurre. In the U.S., she is looking at the complex vocalizations of Monk Parakeets and how they differ between native and introduced individuals. Each parrot has its own distinctive voice with changes in the frequency of its squawks. She found that the introduced parrots have less complex calls than birds in the native ranges. "Something about their environment might be constraining their ability to produce or perceive these vocal signatures," she says. How permanent are the changes, she wonders? Would an introduced parrot be able to return to its native range and thrive?

For better, for worse, and sometimes both, parrots have taken over our cities. Their ability to thrive in our altered habitats is a testament to what makes these species special and why we should work to conserve them in the wild while minding the potential impacts of introduced parrots. They're innovators, problem solvers, socializers and survivors. That's how they earned our adoration in the first place. Sometimes it's a joy to stop and marvel at the parrots. SA

FROM OUR ARCHIVES

Cockatoos Work to Outsmart Humans in Escalating Garbage Bin Wars. Darren Incorvaia; ScientificAmerican.com, September 12, 2022.

scientificamerican.com/magazine/sa

NEUROSCIENCE

Synchronized Minds

The brains of social species are strikingly resonant

By Lydia Denworth

Illustration by Samantha Mash

Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American.* She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

NEUROSCIENTISTS USUALLY INVESTIGATE ONE BRAIN AT A TIME. THEY observe how neurons fire as a person reads certain words, for example, or plays a video game. As social animals, however, those same scientists do much of their work together—brainstorming hypotheses, puzzling over problems and fine-tuning experimental designs. Increasingly, researchers are bringing that reality into how they study brains.

Collective neuroscience, as some practitioners call it, is a rapidly growing field of research. An early, consistent finding is that when people converse or share an experience, their brain waves synchronize. Neurons in corresponding locations of the different brains fire at the same time, creating matching patterns, like dancers moving together. Auditory and visual areas respond to shape, sound and movement in similar ways, whereas higher-order brain areas seem to behave similarly during more challenging tasks such as making meaning out of something seen or heard. The experience of "being on the same wavelength" as another person is real, and it is visible in the activity of the brain.

Such work is beginning to reveal new levels of richness and complexity in sociability. In classrooms where students are engaged with the teacher, for example, their patterns of brain processing begin to align with that teacher's—and greater alignment may mean better learning. Neural waves in certain brain regions of people listening to a musical performance match those of the performer—the greater the synchrony, the greater the enjoyment. Couples exhibit higher degrees of brain synchrony than nonromantic pairs, as do close friends compared with more distant acquaintances.

But how does synchrony happen? Much about the phenomenon remains mysterious—even scientists occasionally use the word "magic" when talking about it. One straightforward explanation could be that coherence between brains is a result of shared experience or simply a sign that we are hearing or seeing the same thing as someone else. But the newest research suggests that synchrony is more than that—or can be. Only by looking into the brains of all individuals involved in an interaction, says neuroscientist Weizhe Hong of the University of California, Los Angeles, can we start to "fully understand what is going on."

Researchers are discovering synchrony in humans and other species, and they are mapping its choreography—its rhythm, timing and undulations—to better understand what benefits it may give us. They are finding evidence that interbrain synchrony prepares people for interaction and beginning to understand it as a marker of relationships. Given that synchronized experiences are often enjoyable, researchers suspect this phenomenon is beneficial: it helps us interact and may have facilitated the evolution of sociality. This new kind of brain research might also illuminate why we don't always "click" with someone or why social isolation is so harmful to physical and mental health.

RESONANCE

THOSE TANTALIZING PROSPECTS are why, last December, I put on a pair of hospital scrubs and lay in the tube of a functional magnetic resonance imaging (fMRI) machine at Harvard University. As instructed, I tried to keep as still as possible with my head in a cradle and my left thumb poised on an emergency call button. It was as uncomfortable as I had been warned it would be.

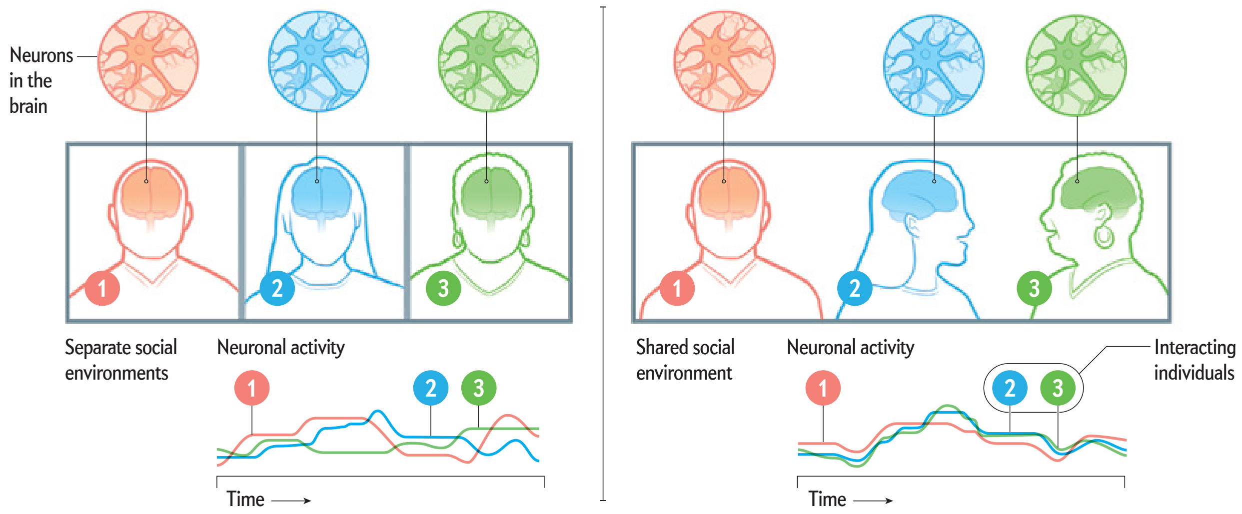
"Are you okay?" asked a muffled voice from the control room next door.

What Is Brain Synchrony?

When people are not interacting socially, their individual brain waves are quite different (*left*). But when they think, feel and act in response to others, patterns of activity in their brains align (*right*).

Scientists call this phenomenon interbrain synchrony. Neurons in the different brains fire simultaneously—and as the interaction continues, the timing and location of brain activity become more and more alike.

The extent of synchrony indicates the strength of a relationship, with brain-wave patterns matching particularly well between close friends or an effective teacher and their students.



"I'm good," I lied.

Then a new, louder voice sounded in my earbuds: "Can you hear me?"

This was Sid. He was going to be my conversation partner for the next hour.

We introduced ourselves. I said I was a science journalist. He said he worked in a social neuroscience laboratory at Dartmouth College. Sid and I were communicating via the Internet as we lay in separate brain-imaging machines 130 miles apart.

Instructions flashed on the screens above each of us. Our task was to tell a story together in alternating turns of 30 seconds each. I was to go first using this prompt: "A group of children encounters aliens."

I launched into a story about children on a school field trip who went for a walk in a park with their teachers and stumbled on the dramatic landing—loud noise, bright lights—of an alien spaceship. Sid had some of the braver children venture closer, led by a boy named Kevin. I added a girl named Annabel who reached out a finger to touch one of the creatures. Sid threw in some hints of ancient connections between the two worlds.

Eventually the counter on the monitor above me flashed: 4 … 3 … 2 … 1 … time was up. New instructions appeared. Now we each had to build our own story in 30-second increments. Between our own increments, we were to listen to the other person's evolving tale. When that was done, we both had to retell all three stories: our joint creation and the ones we invented separately.

The story Sid and I told together wasn't terribly original. My solo effort, about a kid who got in trouble, was even less so. But one thing stood out: I found it far more fun to work together than alone—so much so I forgot about my discomfort. When I met Sid in person the next day at Dartmouth, he agreed. He, too, had enjoyed telling a story with me more than telling his own tale.

That seemed fitting to Dartmouth neuroscientist Thalia Wheatley, who had enlisted us in this pioneering study. While Sid and I did our thing, Wheatley, her postdoctoral researcher JD Knotts and Adam Boncz of the Research Center for Natural Sciences in Budapest listened and watched from control rooms at Harvard and Dartmouth while multiple computers recorded what Sid and I said, when we said it and what our brains were doing at the time. The fMRI machines we were in tracked changes in blood flow throughout the brain, which correlate tightly with changes in neural activity. The results of such imaging highlight, albeit indirectly, *where* in the brain things are happening. For instance, the auditory cortex should be active while a person is listening, but so should areas in the temporal lobe that process language and meaning.

Later the research team would pore over the voluminous data generated, hoping to see the ways two brains, together, change as they interact and might even make something new. "When we're talking to each other, we kind of create a single überbrain that isn't reducible to the sum of its parts," Wheatley says.

Graphics by Now Medical Studios

Scientists are hoping to see the ways in which two brains in conversation change as they interact and might even make something new.

"Like oxygen and hydrogen combine to make water, it creates something special that isn't reducible to oxygen and hydrogen independently."

At least that is the idea. To see whether they can pinpoint that "something special," the researchers will compare the activity in my and Sid's brains, and the brains of all the other pairs in the study, second by second, voxel by voxel over the course of our storytelling session, looking for signs of coherence. They will also consider the questionnaires and reports about the experience we and other participants filled out after we emerged from the machines (using questions such as "How much did you like the story you created with your partner?"). Such studies take time, but in a year or so, if all goes according to plan, they will publish their first results.

The initial "hyperscanning" study—two people, two fMRIs—took place at the Baylor College of Medicine in Houston. Neuroscientist Read Montague, now at Virginia Polytechnic Institute and State University, put two people in separate fMRI scanners and recorded their brain activity as they engaged in a simple competitive game. The relatively limited goals of that experiment were to demonstrate the feasibility of following simultaneous activity in two brains and to identify technical hurdles. The results were published in 2002. Since then, the field has gotten better at hyperscanning with fMRI and expanded to other kinds of technology.

Like fMRI, functional near-infrared spectroscopy (fNIRS) tracks changes in oxygen levels in blood flow; because oxygenation increases with energy demands, scientists can use the method to track brain activity. Employing just a cap of lights and sensors—oxygen-rich blood interacts with light differently than less oxygenated blood does—fNIRS is cheaper and less demanding to administer than fMRI. It is, however, also more limited because it reaches only the upper levels of the brain.

Electroencephalography (EEG), another type of scan, zeroes in on timing, recording the speed and sequence of brain activity—focusing on the *when* more than the *where* revealed by fMRI. EEG also reflects the relative pace of different types of brain waves or oscillations. Like waves in water, waves in the brain rise and fall in cycles fast and slow. The five common brain-wave types, named alpha, beta, gamma, delta and theta depending on their oscillation rate, signify different states of the brain. At 0.5 to four hertz (one hertz is a full oscillation per second), delta waves usually represent deep, restful sleep. Other waves are fast and choppy—awake and conscious activity is typically associated with beta (13 to 30 Hz) and gamma waves (roughly 30 to 100 Hz).

New studies similar to Wheatley's aim to go beyond the early findings and ask, for example, whether storytelling pairs who build better stories show more tightly coupled brain activity than those whose efforts fall a little flat. For the findings to count as "extra" during the joint storytelling condition, correlations between brains "should not be linked simply to people speaking or listening and understanding each other on a linguistic level," says Boncz, who is a co-lead on the study I took part in. "It should be something more."

To establish the neural underpinnings of interacting brains, neuroscientists are also turning to other species in which they can investigate at deeper levels of neurobiological detail than in humans. Among the social mammals they are studying, some of the most intriguing—and surprising—are squabbling, snuggling, swooping bats.

BAT-BRAINED

IT IS NOT HARD to find Michael Yartsev's lab at the University of California, Berkeley. Small, black, plastic bat wings are pinned to the wall by his nameplate as if they were fluttering around his door. Here it is always Halloween. And it was here, in 2019, that Yartsev and postdoctoral researcher Wujie Zhang were the first to show that bat brains synchronize just as human brains do. Although scientists have long studied collective behavior in animals from insects to mammals, they had never reached the level of the brain in this way.

Yartsev's groundbreaking study showed what is probably the simplest of the multiple levels of meaning synchrony carries: it is a strong signal of social interaction. In bats, it is present only when they are together.

The bats live downstairs, in what Yartsev, who is both a neuroscientist and an engineer, affectionately calls the "bat cave." He houses around 300 fruit bats in two colonies, one for males, the other females. The walls of the colony rooms are black, and in each there are mesh panels attached to the ceiling and netting spread throughout the room. Upside-down fruit kebabs of cantaloupe and apple hang from the ceiling, as do blue plastic structures for the bats to play in.

Yartsev was drawn to the study of fruit bats because of their vocal learning and communication skills, but he quickly realized they offered a window into sociality, too. Standing in the doorway of a colony room and watching the bats hang out together, it's not hard to see why. Although they have plenty of room to spread out, the brown-gray mammals, each six to eight inches long, usually huddle in clusters, clinging to the netting or hanging from the mesh.

In the wild, these highly social fruit bats spend their nights foraging for food and much of the day sleeping in big, crowded colonies in caves or trees—sometimes with hundreds or thousands of other bats. While packed in tightly, they squabble over food, sleeping space and mating attempts.

Down the hall from the colony rooms at Berkeley, there's a large "flight room" for experiments. While Yartsev and I watch, graduate students carry in two plastic containers with lids and release a group of bats. From the control room next door, the animals show up as dots on the computer monitors, looking like remote-control Ping-Pong balls zinging around the room and occasionally coming to rest in odd corners.

Studying free-flying bats as Yartsev does is an exercise in technical precision. Because the bats spend so much time huddled together and fly so quickly, it can be hard to identify them or figure out which bat vocalized. To track location, behavior *and* brain activity, the scientists outfitted the flight room with 16 cameras and multiple antennas hidden in small white boxes. Tiny transponders hanging around each bat's neck have microphones that help the team detect which bat is vocalizing, and the cameras detect their locations at resolutions of a centimeter or less. Brain activity is monitored separately via electrodes recording from a variety of brain regions and feeding neural data into tiny, lightweight loggers attached to each bat's head. When the experiment is done, the information from each logger is uploaded and analyzed.

In Yartsev and Zhang's 2019 synchrony experiment, they used wireless electrophysiology and other technology to track bats' behavior and brain activity for about 100 minutes at a time. They saw that the bats' behavior was roughly correlated—they tended to rest at the same time and be active at the same time. Their active periods included social and nonsocial behaviors such as fighting or grooming themselves or one another.

To compare brain activity, the scientists analyzed a spectrogram of all brain-wave activity. What stood out in the bats was that high-frequency bands (from 30 to 150 Hz) had more power, or prominence, during periods of active behavior, and low-frequency bands (1 to 29 Hz) had more power during rest. It was also immediately obvious—strikingly so—that there were very high levels of interbrain synchrony among the bats, especially at high frequencies. The patterns were so similar that the researchers initially didn't believe what they were seeing, but the data convinced them. "Here's signal number one, and here's signal number two," Yartsev says. "Just do the correlation between them. It was so incredibly robust, which was very reassuring because it suggested we were looking at something real. We would see it every single time when they were socially interacting."

When Yartsev and Zhang repeated the experiment by letting the bats fly freely in identical separate chambers rather than in the same social environment, the correlations fell apart. There was no synchrony in the bats' brain activity, even when the researchers piped in the sound of other bats calling. And there were more intriguing details. In social situations, the correlations increased as bats interacted more. And increases in correlation between brains preceded increases in social interaction—a reflection of the fact that each interaction is a series of decisions, suggesting that brain correlation facilitates interaction.

Yartsev and Zhang concluded that there is something special about social interaction. Synchrony may be a sign of shared cognitive processing, which is the chemical and electrical signaling in the brain that allows individuals to comprehend their environment, communicate and learn.

NEURON BY NEURON

LOOKING AT SYNCHRONY between bands of brain waves is one way of understanding what's going on between interacting brains. Another is to look at the activity of specific neurons. "Ultimately our brains are not a soup of averages. They consist of individual neurons that do different things, and they may do opposite things," U.C.L.A.'s Hong says. Hong and his colleagues were among the first to go looking for this level of detail and study interacting brains neuron by neuron. What they found revealed even more complexity.

Like Yartsev, Hong first doubted that the interbrain synchrony he and his team observed in animals—in their case, mice—was real. He hadn't yet read the literature on synchrony in humans and told Lyle Kingsbury—at the time a student of Hong's and the lead scientist on the research and now a postdoctoral fellow at Harvard University—that there must be something wrong. There wasn't. Using a technology called microendoscopic calcium imaging, which measures changes in induced fluorescence in individual neurons, they looked at hundreds of neurons at the same time. In pairs of interacting mice, they established that synchrony appeared during an ongoing social interaction. Further, synchrony in mouse brains arose from separate populations of cells in the prefrontal cortex, which Hong calls "self cells" and "other cells." The former encodes one's own behavior, the latter the behavior of another individual. "The sum of activity of both self and other cells is similar to or correlated with the sum of activity in the other brain," Hong says.

What they are seeing goes well beyond previous research on so-called mirror neurons, which represent both the self and another. (When I watch you throw a ball, it activates a set of mirror neurons in my brain that would also be activated if I were doing the same thing myself.) In contrast, the self and other cells Hong and Kingsbury discovered encode only the behavior of one individual or the other. All three kinds of cells—mirror, self and other—were present and aligning in the mouse brains.

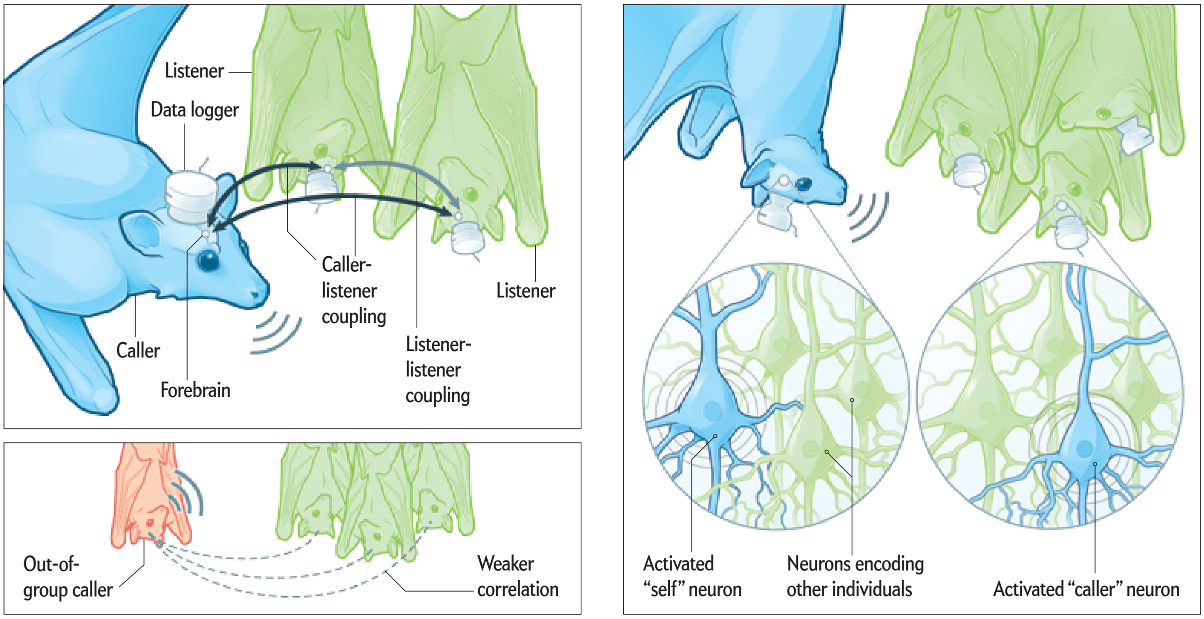
The mouse study suggested another level of meaning for synchrony: it predicts the outcomes of future

Coupled Bat Brains

Bats are social animals, and when together, their brain waves synchronize. Investigators at the University of California, Berkeley, recorded neuronal activity from four Egyptian fruit bats as they freely interacted—flying, squabbling and resting. Synchrony was strongest among "friend" bats that hung out together. The data also revealed which neurons coded for which individual bat.

When one bat emits a call, it induces collective brain coupling among all listening bats. Scientists found the synchrony to be strongest among bats that tended to hang close together.

The calls also activated a separate set of neurons, depending on which bat in the group was calling. These neurons encoded identity, with some representing the self and others representing the caller.



Source: "Cortical Representation of Group Social Communication in Bats," by Maimon C. Rose et al., in *Science*, Vol. 374; October 22, 2021 (*reference*)

interactions. Like bats, mice enjoy the company of other mice and sleep huddled together, but they are a hierarchical species, with some animals more dominant than others. To take advantage of that, Hong and Kingsbury used a standard experiment called a tube test that is much like watching two football teams try to reach each other's end zones. The researchers placed two animals in a tube, one at each end, and watched them advance toward each other. They wanted to see which mouse gained the most ground on its opponent. The one who got farther was deemed dominant.

Surprisingly, there were higher levels of synchrony between mice who were further apart in social status—one dominant and one submissive—and lower levels between mice closer in rank. (Researchers in China found something similar in human leaders and followers. In a 2015 study, neural synchronization was higher between leaders and followers than between followers and followers.) Once they recognized the role of social status in their experiment, Hong and Kingsbury could use the levels of synchrony they observed to predict within a few minutes of a 15-minute interaction whether one mouse would dominate and how much more progress it would make.

It's not entirely clear how hierarchical bats are, but they do have preferred companions. Yartsev and his team noticed that most of their bats tended to cluster together, but there were a few that spent their time a little off to the side. The researchers set out to see whether there were differences in levels of correlation when "in-cluster" and "out-of-cluster" bats vocalized. This time, in addition to recording brain activity at the level of frequency bands, they also recorded the activity of individual neurons in the brains of four bats simultaneously as they flew in groups of four, five and eight. A 2021 study led by Maimon Rose and Boaz Styr, then both members of Yartsev's lab, revealed that when one bat emits a call, it induces collective brain coupling among all listening bats. And as in the mice, separate sets of neurons became active depending on which bat in the group vocalized, meaning individual neurons in the bats' brains encoded identity, with some representing the self and others representing other individuals. The signals were so distinct that the scientists could tell which bat was calling just by looking at the recordings of neural activity. Correlation among brains was visible in all the bats, but it was strongest when calls came from "friendlier" bats—those that clustered together more often.

The bat and mouse studies were technically very different, but "the two stories are surprisingly similar," Hong says. "This is the exciting part of science when you see someone else's work support the conclusions we have [made] independently."

Synchrony may help people teach and learn, forge friendships and romances, cooperate and converse, and even maintain emotional stability.

BEYOND SYNCHRONY

THE GOAL of the latest human studies, such as the one Wheatley invited me to join, is not just to explore synchrony more deeply but to go beyond it. Wheatley, who with four other Dartmouth scientists is establishing the college's Consortium for Interacting Minds, believes that asking when we are in sync with someone else is "a pretty limited way to think about two minds coming together." More interesting, Boncz says, would be to see whether brains can align at the level of understanding. "We think there could be synchrony, for example, when people understand perhaps even different stimuli the same way, if they have some sort of higher-level meaning that they share."

The preliminary evidence from the study in which I participated shows synchrony between interacting brains and, more intriguingly, that correlations in some brain regions are greater between people while they are telling a joint story than during the independent stories, particularly in the parietal cortex. "That area is active for memory and narrative construction," Wheatley says. "It seems to fit."

But the group is also asking whether the content of the stories changes levels of alignment and whether each pair's relative enjoyment of the process is linked to a greater or lesser degree of synchrony. Like Sid and me, most people reported preferring the joint storytelling exercise to the individual tales, but that wasn't true for everyone. Are synchronized brains more creative? Or do they just have more fun? The answers will have to wait for further analysis.

One of the challenges of this study is making sense of the mountain of data it generates. Like early astronomers mapping constellations in a star-filled sky for the first time, the scientists have to find order in seeming chaos by making sense of it mathematically. Measuring synchrony is relatively straightforward, Wheatley says, because "we know how to do that math." The researchers calculate linear correlations between subjects to determine the degree to which parts of their brains respond in the same way over time—are they in lockstep? Does their activity ebb and flow together?

The hyperscanning study is only one way Wheatley is approaching synchrony. In a forthcoming study, available as a preprint, she and Beau Sievers, who is currently working as both a research associate at Harvard and a postdoc at Stanford University, show the power of conversation to synchronize brain patterns. Forty-nine participants watched unfamiliar silent movie clips, then split into small groups of about four people to discuss the clips. Each group was asked to reach a consensus on what the movies were about. After the conversations, the groups watched the clips again, as well as new video from the same movies. After further discussion that reached consensus, patterns of brain processing aligned across participants as they watched the second round of videos. Members of a conversational group had the same brain activity at the same time in brain areas handling vision, memory and language comprehension. The people who listened and worked hardest to seek consensus—and not those who talked most—were the ones whose brains synchronized with others first and who drove synchrony in the larger group. "By talking together and coming to consensus as a group," Sievers said in a video describing the study, "participants aligned their brains."

Taken together, these findings are an intriguing way of understanding how our brains facilitate the social interaction that is so critical to human life. Without synchrony and the deeper forms of connection that lie beyond it, we may be at greater risk for mental instability and poor physical health. With synchrony and other levels of neural interaction, humans teach and learn, forge friendships and romances, and cooperate and converse. We are driven to connect, and synchrony is one way our brains help us do it.

Cooperating and conversing are what Sid and I were doing in our separate scanners as we created a story together. More impressive than our effort, though, was that of the pair who came before us. Caitlyn Lee, a graduate student in Wheatley's lab, was working with Lorie Loeb, a computer science professor at Dartmouth. They set their story not in a park, like ours, but in an unfamiliar landscape. During one of her turns, Lee said, "The trees [the children] were climbing on looked really weird; the ground was starting to rise." Then her turn cut off, and Loeb picked the story up, saying, "It felt like the creature took a breath." It was exactly what Lee had been thinking: that the children were walking on the alien itself. "It really felt like we were on the same page," Lee says.

As we listened to Lee's retelling, Wheatley turned to me. "At some level," she said, "I think it has to be the synchrony." SA

FROM OUR ARCHIVES

All Together Now. Marta Zaraska; October 2020.

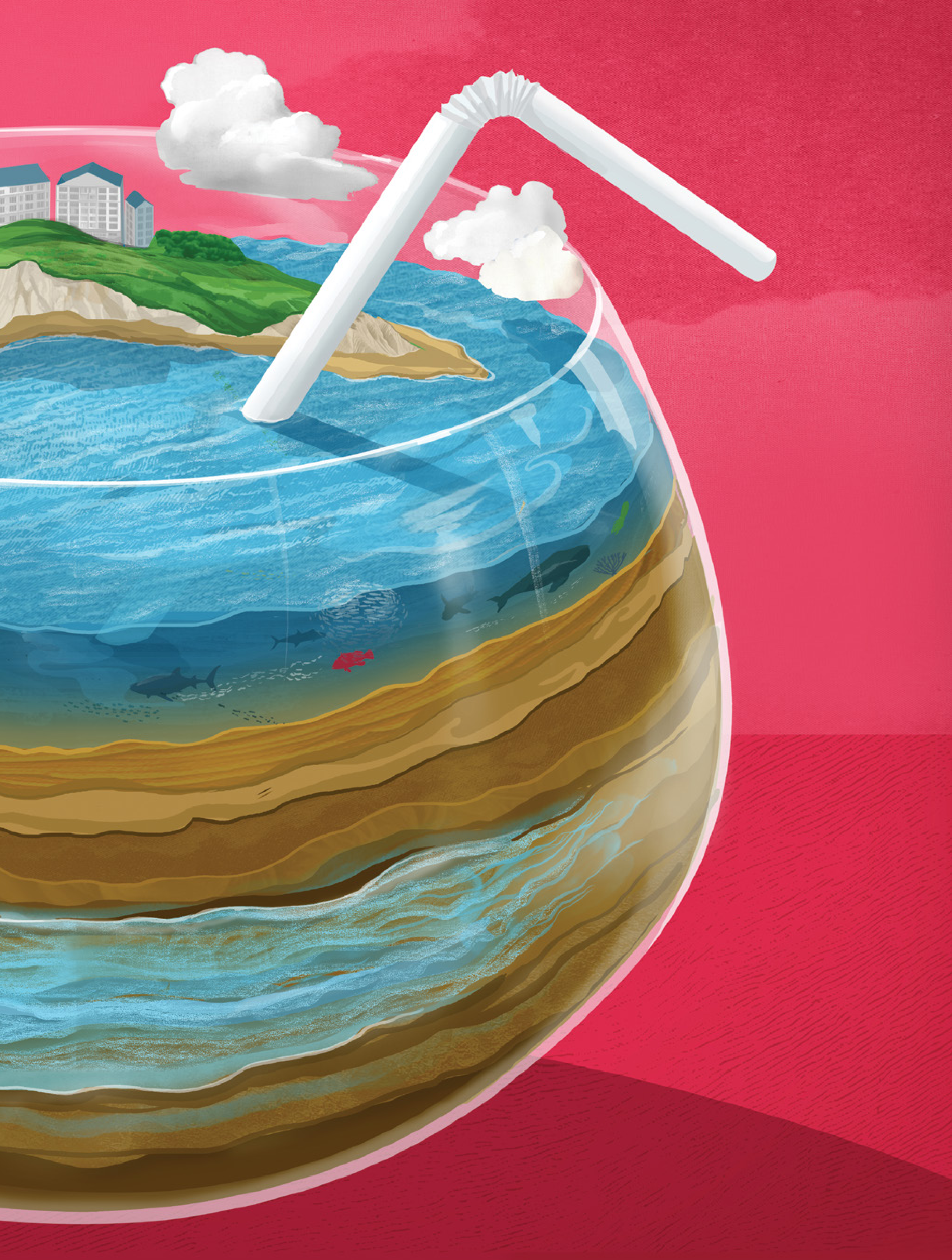
scientificamerican.com/magazine/sa

Undersea Aquifers

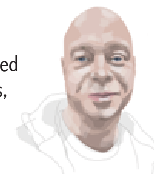
Researchers are discovering giant deposits of fresh water below the coastal seafloor that might someday save dry regions from drought

By Rob L. Evans

Illustration by Sam Falconer



Rob L. Evans is a geophysicist and a senior scientist at the Woods Hole Oceanographic Institution, where he has worked for 29 years. He has sailed on more than 30 research cruises, spending more than two years at sea.



ON A CLEAR SEPTEMBER DAY IN 2015, AFTER 10 YEARS OF WORKING TO GET funding, my colleague Kerry Key and I stepped aboard the R/V *Langseth,* a research ship docked at the Woods Hole Oceanographic Institution in Massachusetts. We were about to lead a 10-day expedition to map a deposit of fresh water, size unknown, hidden 100 meters (about 330 feet) under the rocky seafloor.

Back in the 1960s the U.S. Geological Survey had drilled a series of vertical boreholes off the New Jersey coast, looking for sand deposits and other resources. They unexpectedly struck fresh water, which was baffling. Years later researchers obtained water samples from the same location and analyzed the chemistry, finding to their surprise that the liquid was a mix of recent rainwater and seawater. Rainwater, 65 kilometers (40 miles) out to sea—under the seafloor?

That's where we were headed. Once the R/V *Langseth* was in position, we spooled out a long, floating line that held a special transmitter. It sent electromagnetic fields hundreds of meters down through the ocean and into the seabed. The fields passed through the seafloor and created secondary, return signals captured by other sensors on the line. We slowly towed the array for 130 kilometers over the region where drilling had been done. We also dropped instruments that sank to the bottom and recorded the signals from our transmitter, as well as naturally occurring electromagnetic fields. We could use all these readings to create an image of what was underneath the seafloor. Once we had completed the survey off New Jersey, we sailed up toward Martha's Vineyard—where researchers had suggested there might also be fresh water—and ran a long sensing profile there, too.

It took us months to process all the data. When we published our results in 2019, we made a stir. One media headline summed up the excitement: "Mysterious Freshwater Reservoir Found Hidden beneath the Ocean." True. But how big was it? How did it get there? And how common are these offshore underground deposits? We didn't know.

Other questions nagged us. Only about 2.5 percent of all the surface water on this ocean planet is fresh. As the global population grows toward an estimated 10 billion people by 2100, the stresses on our water supply will increase—especially in coastal regions, where 30 percent of the U.S. population now lives. Climate change is also altering rainfall patterns, pollution is compromising extant bodies of water, and agriculture and development are sucking underground reservoirs dry. Could large, hidden reservoirs only a few dozen kilometers out to sea save lives and help irrigate dry crops? Do such reservoirs exist around the world in places where water scarcity is already a huge challenge? If so, could we tap these surprising deposits safely and economically? Our discovery prompted further studies, including recent surveys off San Diego, Hawaii, New Zealand and Malta that are starting to provide answers.

BURIED AT SEA

RECORDS OF FRESH WATER being found offshore go as far back as the 1800s. Fishers off Florida have occasionally reported "boils" of water on the ocean's surface, which they assume leaked upward from below. In some cases, they sampled the water and it did not taste salty; fresh water is less dense than seawater, so it rises.

In 1996, two years after I started at Woods Hole, I was on a small chartered research vessel with six colleagues offshore of Eureka, Calif., the coastline still visible in the distance. We were using a new seafloor-surveying system that had been built at the Pacific Geoscience Center in Canada to map sediments. Our study was part of a large program looking at how flooding rivers that flow to the shoreline disperse sediment into the sea, and our equipment was measuring the amount of seawater in sediment to depths of about 30 meters. It used electromagnetic sensing, a technique that was on the fringes of marine geophysics.

In one area where all other data made us think we should see fine-grained, muddy sediments with high saltwater content, we saw a signal that insinuated the opposite: the reading suggested fresh water that extended for about 50 square kilometers, a sign that groundwater might be leaking from below the shore and oozing through cracks and faults extending into the seafloor. The discovery made us realize that electromagnetic sensing could detect fresh water hiding anywhere under the sea.

A continent does not stop at its shoreline; it extends well offshore as a rocky underwater shelf. The shelf ends at a steep slope that transitions sharply to deep oceanic seafloor. The rock and sediments that make up the world's continental shelves are not dry. Some rocks crack, allowing seawater to penetrate. And most shelves are covered by layers of sedimentary rock, which are like hard sponges with small, interconnected, water-filled pores.

Sediments at or just below the seafloor are typically 40 to 50 percent porous. The weight of the ocean above pushes water down into the sediment as far as it can go. Geoscientists still debate the maximum depth, but it can be at least several kilometers, although the seepage decreases rapidly with depth as the increased pressure closes up cracks and pore spaces. The rock's permeability—the ease with which water can flow through it—depends on how extensively its various pores are interconnected.

Because the shelf is a continuation of the continent, models of groundwater flow in land along the northeastern U.S. coast suggest there could be substantial amounts of fresh water hidden within the rocks and sediments below the continental slope's seafloor. But there are competing hypotheses about how such water might get there—and remain there.

On land, subsurface water is stored in geologic layers of water-bearing rock called aquifers. Some aquifers are shallow and can be replenished by rainfall. Others are much deeper and hold water that has been in place for thousands of years, perhaps left there by glaciers during the last ice age. The composition of aquifers varies across regions, from limestone layers below Florida to more sedimentary layers in the Northeast. Groundwater—the fresh water contained in aquifers—makes up roughly 90 percent of the total available fresh water in the U.S., even when we factor in rivers and lakes. About 25 percent of the water consumed in the U.S. is pumped from aquifers through private or municipal wells.

Off the U.S. East Coast the continental shelf extends anywhere from close to shore to more than 300 kilometers out to sea. Perhaps not surprisingly, the geologic layers that form aquifers under land do not stop at the shoreline; they often extend outward as part of the shelf.

When rain falls on coastal land, it can percolate down into an aquifer and through highly permeable rocks, traveling under and across the shoreline and eventually out to the seabed. For this long-distance flow to occur and for the water to remain fresh, there needs to be a cap over the marine aquifer—a layer that is not permeable, usually of compacted clay-rich sediment. Clay is paradoxical: it can hold a lot of water when loose, but when it is compacted it becomes almost impervious. This cap prevents the less dense fresh water from rising up to the seafloor.

An entirely different mechanism could also leave fresh water under the seafloor. During past ice ages, giant ice sheets and glaciers grew, soaking up large volumes of ocean water. Sea level was much lower, and long sections of continental shelves were exposed as land open to the elements. During the last ice age, roughly between 12,000 and 20,000 years ago, rain falling on these areas could have percolated down into the subsurface, just as it does onshore today. If that water flowed underneath a cap, it could have remained trapped as the ice sheets later melted and sea levels rose again. Yet another model posits that the great weight of the ice sheets pushed fresh water deep into the subsurface and below caps.

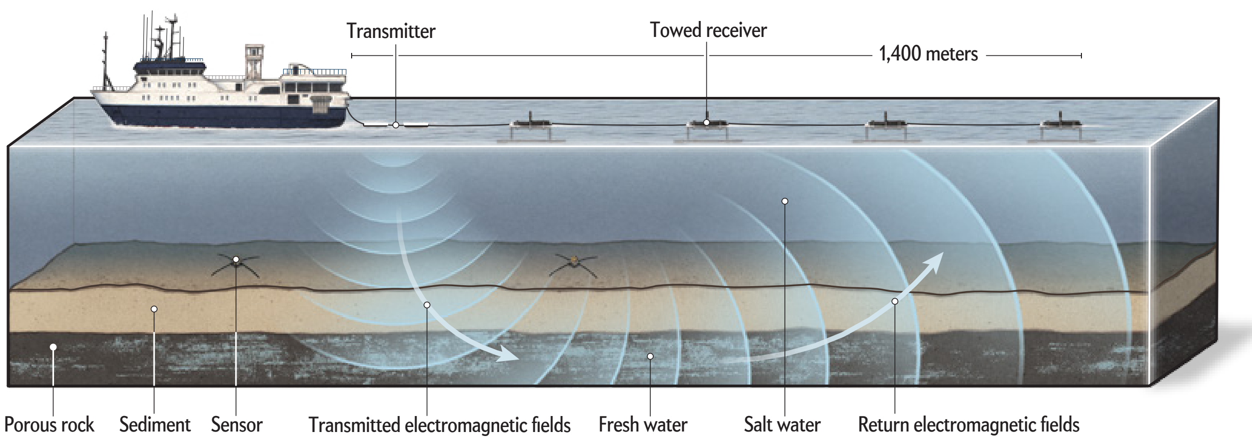
FRESH OR SALTY

FIGURING OUT HOW a specific reservoir formed—whether it is connected to aquifers on land and how extensive it may be—requires a lot of sensing. Drilling provides samples, but it is expensive and limited to isolated spots. What had been missing until our cruise on the R/V *Langseth* was a relatively inexpensive, easy-to-use technique that could cover large areas of seafloor.

In the 1970s and 1980s researchers began developing electromagnetic instruments to measure properties of the seafloor, motivated in part by the U.S. Navy's interest in long-distance submarine communications. Through the 1980s and 1990s "controlled source electromagnetic" (CSEM) sensing slowly became more sophisticated. In the late 1990s and early 2000s the petroleum industry began using the technology to detect subsurface

Finding Wet Treasure

Electromagnetic fields transmitted from a ship down into the seabed travel within the rocky substrate, generating a return signal picked up by floating receivers. The signal varies, with salt water in rock cracks and pores conducting electric current better than fresh water, revealing where fresh water is lurking. Sensors on the seafloor aid the process.



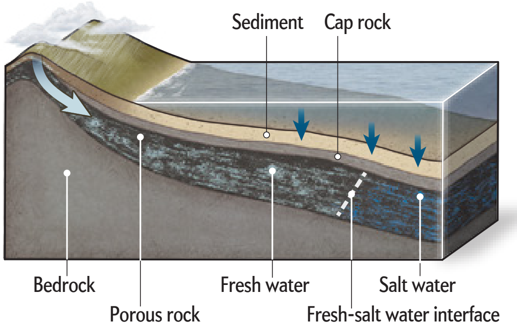
Graphics by Julia Ditto

How Water Seeps into the Seabed

Fresh water may become trapped under the seafloor in several ways. It might be trickling out there today from underground aquifers on shore (*top*), or it might have accumulated millennia ago during past ice ages (*middle* and *bottom*). In each case, a layer of cap rock separates it from ocean water percolating down from above.

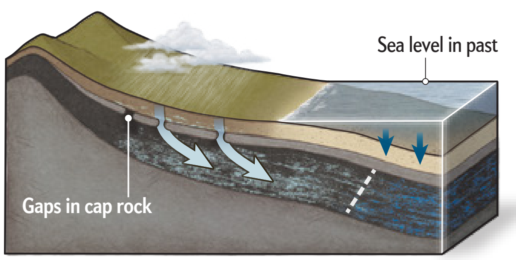
Subsurface Connections from Shore

Fresh water in underground aquifers on land can seep through fissures and porous rock that extend out under the seafloor. Impervious cap rock prevents salt water from intruding.



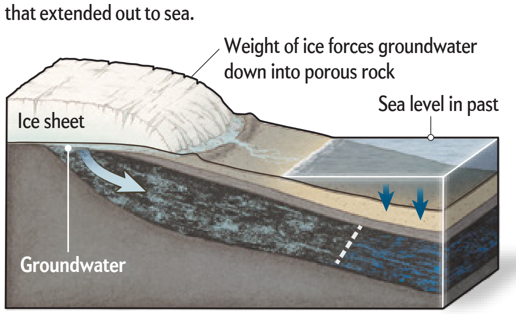
Rainfall during Low-Sea-Level Period

When sea level was low during ice ages, rain may have fallen on exposed seafloor sediment and filtered down through gaps in the cap rock, into porous rock below.



Ice-Sheet Pressure during Low-Sea-Level Period

When sea level was low, the tremendous weight of ice sheets onshore may have forced groundwater down into porous rock that extended out to sea.



Source: "Origin and Extent of Fresh Paleowaters on the Atlantic Continental Shelf, USA," by Denis Cohen et al., in *Ground Water*, Vol. 48; January–February, 2010 (*reference*)

oil, which drove significant improvements in the instrumentation available to researchers.

CSEM sensing basically measures how well the seafloor conducts electric current. In the continental shelf, electrical conductivity is controlled by the amount of seawater in pores and cracks, as well as the salinity and temperature of that seawater. The sodium and chloride ions in salt are charge carriers that enhance conductivity, so salt water conducts better than fresh water. A section of ocean floor infused with seawater will conduct current better than a section infused with less saline water. CSEM can measure the differences with fairly high precision.

During our cruise the four receivers on the tow line were 600 to 1,400 meters behind the ship. They measured the electric field generated by the transmitter near the ship, as well as an induced electric field that was detected as it returned from the seafloor substructure. The farther back the receiver, the deeper it could look into the subsurface. That information, along with data about Earth's naturally occurring electric and magnetic fields from the instruments we dropped on the seafloor, allowed us to clearly show that there are submarine freshwater aquifers off New Jersey and Martha's Vineyard.

We still have no good idea about the extent or volume of fresh water, however. Although CSEM conductivity measurements are sensitive to the salinity of pore water, they are also affected by the porosity of the seafloor—how much water is present in a given volume. A rock with high porosity that is less conductive (fresher water) can have the same reading as a rock with low porosity that conducts current well (saltier water). For our CSEM surveys off New Jersey, we used samples of sediment from the drill holes and samples of the pore water to calibrate our models. Salinity is expressed in grams of dissolved salts per liter. The salinity of seawater is around 35. Water with salinity between 1 and 10 is considered brackish. Anything less than 1 is considered fresh. Pore water salinities off New Jersey and Martha's Vineyard range between 0.2 and 9.0.

We have no data for the seafloor between those places, so we do not know whether the two hidden bodies of water are connected or, if so, how. We think there might be fresh water underneath the entire New England shelf, based on surveys and models of aquifers onshore. The water off Martha's Vineyard may have been left there by glaciers more than 12,000 years ago. The water off New Jersey seems to originate in part from rainfall on land. A large team is making plans for scientific drilling off Martha's Vineyard next year, and that work will provide chemical analyses that could help us figure out how long the water has been hiding there.

Farther south along the Eastern Seaboard, the coastal geology transitions to mostly limestone; the movement of underground water there may be different again. To decipher what is happening, we would need much more CSEM surveying, perhaps augmented by drilling in select locations, which would be a costly undertaking. Surveying the transition from land to sea—to find possible water flows from land aquifers to ocean deposits—is challenging. It would require towing a long array in shallow coastal waters with heavy surf and busy boat traffic, as well as data collection with similar sensors on shoreline land. Although the U.S. East Coast is not under significant water stress compared with other parts of the world, the region is relatively well studied and offers perhaps the best opportunity to understand the various processes involved in offshore groundwater transport and storage.

As I mentioned earlier, other experiments have been conducted since our cruise—some in places that have very different geologic settings. A 2018 survey off Hawaii, using much the same equipment as we used, found clear evidence of rock containing fresh water several hundred meters under the seafloor. Unlike New Jersey, Hawaii is built from volcanic rock, which has relatively high permeability. The assumption, not proved yet, is that the submarine aquifers are created by underground runoff from places on land. Hawaii depends on precipitation for its water supply, so understanding how its water may be lost to the ocean through subsurface routes is important.

TEMPTATION TO TAP

INTEREST IN FINDING offshore freshwater deposits has risen significantly in the past few years, notably in regions where freshwater supplies are scarce. Our best guess at how much is trapped within roughly 150 kilometers of seashores worldwide is about one million cubic kilometers. For reference, New York City consumes about 1.4 cubic kilometers a year. Our guess is based mostly on extrapolation from onshore drill holes, as well as on the few offshore surveys so far.

No one has designed a detailed system to tap a submarine aquifer. Tor Bakken of SINTEF Energy Research in Norway and his colleagues described a general system based on oil-drilling technology. A jack-up rig (basically a platform on legs) or a barge would be anchored above a submarine freshwater aquifer. Engineers would drill into the reservoir, and water would flow through a pipeline on the seafloor to a processing plant onshore. The plant would desalinate the water, probably using reverse osmosis, a common filtering technique. Bakken estimated that this process would be slightly cheaper than desalination of seawater, depending on how salty the "fresh water" is. The desalination, which is energy-intensive, would account for a much larger percentage of the total cost than drilling or pumping the water along the pipeline.

To decide whether to exploit any given offshore water supply, we would need to understand how groundwater finds its way into that patch of seafloor to begin with. Imagine a submarine aquifer that isn't connected to any water-conducting structures under the shoreland. The fresh water is surrounded by sediments containing seawater. As soon as someone started pumping the fresh water out, seawater could flow into the void, mixing with the remaining fresh water and raising its salinity. And once the fresh water is extracted, it won't get replenished.

Pumping water from a submarine aquifer that is connected through a geologic formation to an onshore aquifer could also be risky. Any submarine aquifer would be at least slightly brackish, and pumping could mix the waters, which might reduce the freshness of the land aquifer. Modeling also suggests that excessive pumping of offshore reservoirs could drain the onshore water supplying them and even lead to land subsidence.

Between September 2019 and September 2020 researchers using CSEM sensing showed that brackish groundwater within the San Diego Formation, a big underground supply of water for the city, was connected to a submarine aquifer offshore by Coronado Island. Yet the geology of the region is complex, with a number of faults, which could make tapping a submarine aquifer seem less worthwhile. The U.S. West Coast has many geologic faults that could channel groundwater offshore but that could also allow saltwater intrusion onshore if there were excessive pumping. This would seem to be the case for San Diego.

One million cubic kilometers of fresh water may be stored within 150 kilometers of seashores worldwide. New York City consumes about 1.4 cubic kilometers a year.

All municipalities have a water-supply strategy, usually involving a range of potable water sources, as well as conservation. Some water-stressed regions, including some entire countries, are already desalinating seawater. The process is expensive and, if the machinery is powered by fossil fuels, emits greenhouse gases. Before a locality considered drilling for submarine fresh water, it might consider groundwater that had been dismissed in the past because it was brackish; it might be less salty than the submarine aquifer. San Diego and El Paso, Tex., are already desalinating brackish groundwater. Another issue could be which country has the right to draw from an offshore aquifer that lies across an ocean boundary between two adjacent nations.

Conservation is also important. Everything on Earth's continents and oceans is connected. Onshore groundwater that flows through the subsurface and offshore brings nutrients and chemicals that sustain delicate marine communities in places along the continental slope. We cannot yet predict the environmental consequences of using offshore groundwater as a resource.

Scientists have confirmed only a small number of submarine freshwater aquifers. There could be many more—small, large, refreshed by groundwater or isolated by ice ages. Community efforts are springing up, particularly in Europe, to explore the possibilities. More surveys will gradually solve the mystery—and reveal more surprises. Mapping in 2022 in the Mediterranean Sea around Malta showed an offshore reservoir probably fed by onshore groundwater. The data and modeling concluded that there may be one cubic kilometer of fresh water offshore, enough to supply the population of the Maltese Islands for 75 years. But the modeling also showed that climate change will lessen future rainfall there, reducing offshore groundwater by 38 percent over the next 80 years or so.

We have a lot to learn. Drilling south of Martha's Vineyard next year will tell us much more about how stores of fresh water under land and sea might connect. The more we investigate, the more we will understand about how these hidden treasures are formed, and the better we will be able to predict where we might find them. SA

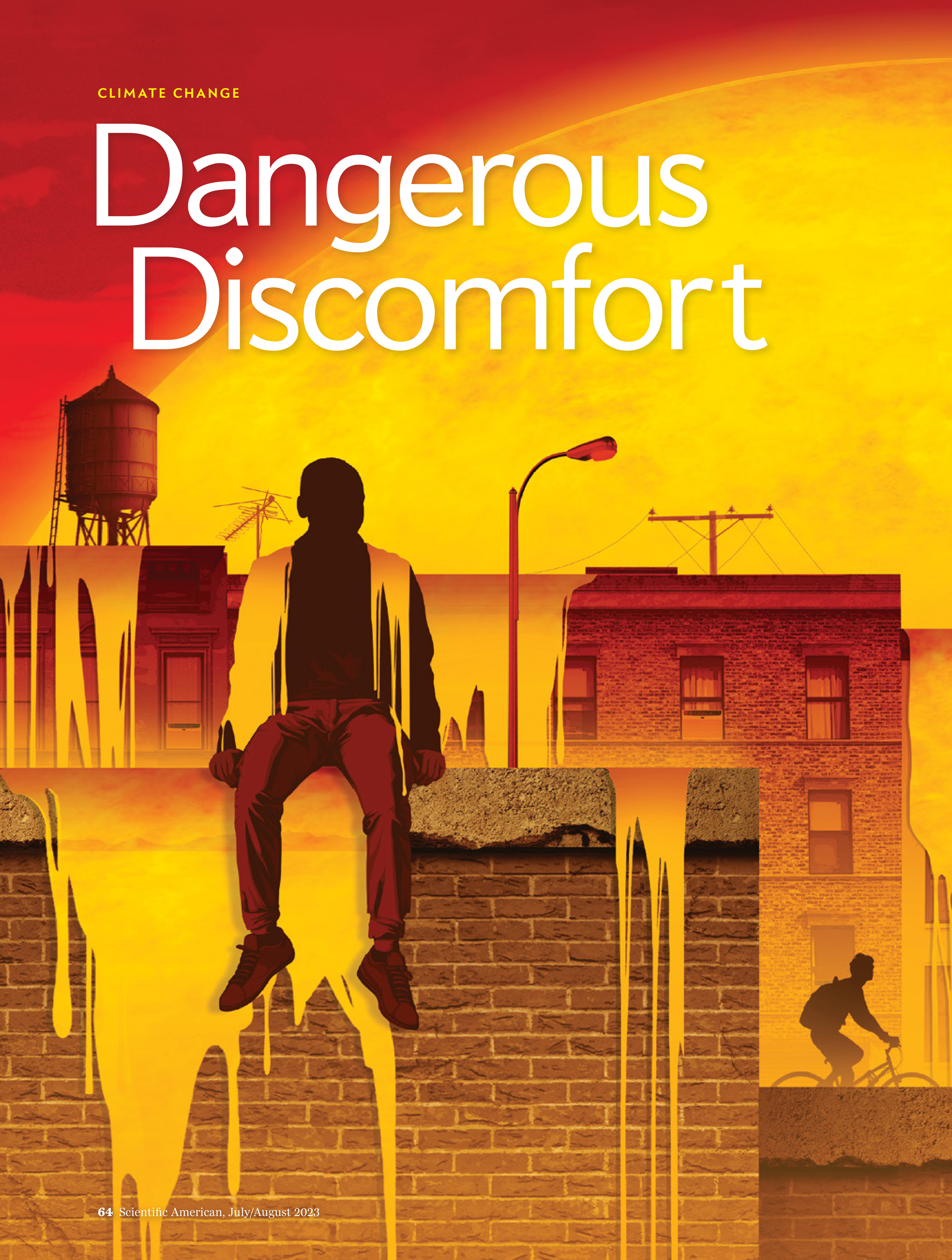
FROM OUR ARCHIVES

Every Inch of the Seafloor. Mark Fischetti; August 2022.

scientificamerican.com/magazine/sa

CLIMATE CHANGE

Dangerous Discomfort

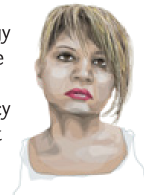


Extreme heat kills more people in the U.S. than hurricanes, flash floods and tornadoes combined. But people don't tend to believe it puts them at risk

By Terri Adams-Fuller

Illustration by Taylor Callery

Terri Adams-Fuller is a professor in the department of sociology and criminology and interim director at the NOAA Cooperative Science Center for Atmospheric Sciences and Meteorology at Howard University. Her research interests include emergency management, policing, gender studies, and how disasters affect people and organizations.



ON JUNE 25, 2022, ESTEBAN CHAVEZ, JR., STARTED HIS DAY LIKE ANY OTHER, working his route in Pasadena, Calif., as a driver for UPS. But the city was in the middle of an intense heat wave, and by midafternoon the temperature was higher than 90 degrees Fahrenheit. After completing his last delivery of the day, Chavez collapsed off his seat in the cab of the truck. He went unnoticed for 20 minutes before the homeowner at his delivery location saw him and sought medical assistance. Chavez's family said he died from heatstroke as a result of heat exhaustion. He was 24 years old.

Chavez didn't seem like someone at risk for the health effects of extreme heat. But such unfortunate deaths are increasingly common. The number of heat-related illnesses and fatalities in the U.S. has been going up since the 1980s—a direct result of the rise in Earth's temperatures. Approximately 1,300 people die in the U.S. every year from exposure to extreme heat, according to the Environmental Protection Agency, and that figure that will almost certainly increase with the accelerating effects of climate change. This phenomenon is, of course, not exclusive to the U.S.; a study published in 2021 by the *Lancet* reports that 356,000 people in nine countries—about half the population of Vermont—died from illnesses related to extreme heat in 2019.

Exposure to extreme heat can damage the central nervous system, the brain and other vital organs, and the effects can set in with terrifying speed, resulting in heat exhaustion, heat cramps or heatstroke. It also exacerbates existing medical conditions such as hypertension and heart disease and is especially perilous for people who suffer from chronic diseases. The older population is at high risk, and children, who may not be able to regulate their body temperatures as effectively as adults in extreme conditions, are also vulnerable. But people of all ages can be endangered. Studies show that outdoor workers regardless of age are most likely to experience the consequences of extreme heat exposure.

Extreme heat is the number-one weather-related cause of death in the U.S., and it kills more people most years than hurricanes, floods and tornadoes combined. Yet research shows that compared with their thinking about dramatic events such as storm surges and wildfires, people tend to feel more uncertain about what to do under the threat of extreme heat and don't perceive as much personal risk. This mismatch between the reality of the danger and the actions people take to protect themselves extends beyond individual perception to the policy level. Heat risks to human health are not often prioritized in climate mitigation and adaptation plans—if they are factored in at all.

DISCRIMINATORY POLICIES AND URBAN HOTSPOTS

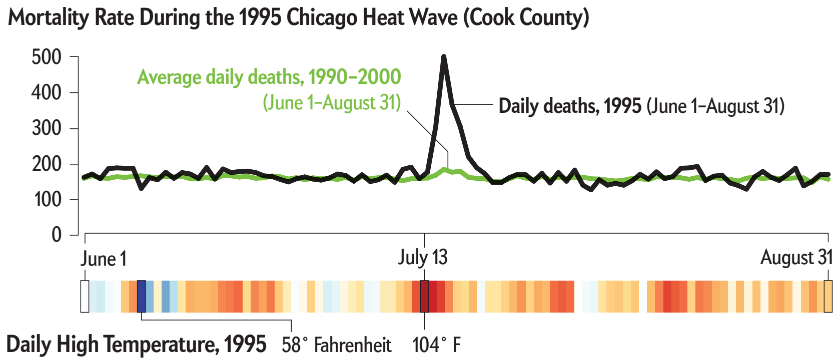
BETWEEN 1880, when precise recordkeeping began, and 1980, average temperatures worldwide rose by about 0.13 degree F every 10 years. Since 1981 the rate of increase has more than doubled, and for the past 40 years global annual temperatures have increased by 0.32 degree F per decade. Although the pace of the increase might seem relatively slow, it signals a dramatic shift, and the cumulative effects on the planet are huge. The 10 hottest years on record have occurred since 2010. The summer of 2022 was the hottest in known history for segments of the U.S. Temperatures soared to 127 degrees F in Death Valley,

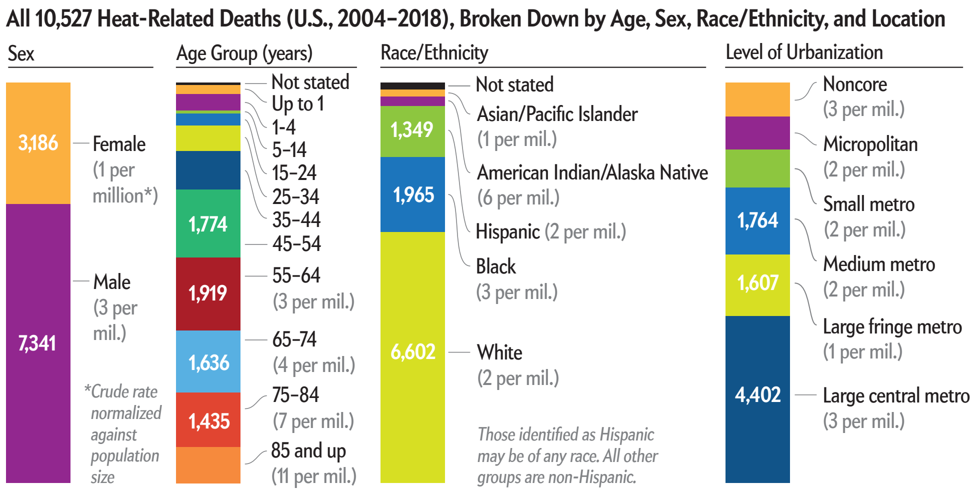
Deaths from Extreme Heat

Extreme heat is the number-one weather-related cause of death in the U.S. Worldwide, the number of fatalities is expected to rise as climate change makes heat waves even hotter and as more and more people move to densely developed urban centers. Yet research has shown that some people have difficulty recognizing the personal risks to their health and safety.

A Clear Surge in Deaths

During a week in July 1995, a heat wave hit Chicago. Daytime temperatures surged to more than 100 degrees Fahrenheit, and nighttime temperatures didn't drop low enough to give people a reprieve. There were about 700 excess deaths between July 11 and July 27 compared with the same period in an average year. The number of deaths classified as "heat related" over this time was 465, suggesting that potentially hundreds of deaths belonging in this category went uncounted. This is one challenge of connecting extreme heat with its true cost in lives.





Some People Are More Vulnerable Than Others

People older than 65 tend to be especially susceptible to the effects of excessive heat; they are several times more likely to die from heat-related cardiovascular disease than the general population. Those who live and work in a densely developed inner city without much green space—areas known as urban heat islands—are also vulnerable. The urban heat island effect can increase temperatures by 18 to 27 degrees F during the day compared with rural areas.

Sources: EPA's Climate Change Indicators in the United States, https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths *(Chicago heat-wave reference, with data from CDC and NOAA)*; "Heat-Related Deaths, United States, 2004–2018," by Ambarish Vaidyanathan et al., in *Centers for Disease Control and Prevention: Morbidity and Mortality Weekly Report,* Vol. 69, No. 24; June 19, 2020 *(heat-related death data)*

Calif., where extremes are expected. But record highs were also reached across the U.S. in cities that aren't accustomed to severe heat, such as Bonners Ferry, Idaho (108 degrees F), and Omak, Wash. (117 degrees F).

Extreme heat is a danger to all segments of society, but people in dense urban environments suffer the most severely. The connection between urbanization and heat risks will become more urgent as more people around the world move to urban areas. According to the United Nations Population Division, 68 percent of the planet's population will live in urban areas by 2050, up from 55 percent in 2018. The rate of global urbanization, however, hides differences across nations: 82 percent of people in North America already live in urban environments compared with 65 percent in China and 43 percent in Africa. In the U.S., the rate of urbanization (people moving from rural areas to cities) increased from 50 percent in the 1950s to 83 percent in 2020. This rapid growth on top of environmental changes compounds stressors on human health, infrastructure, socioeconomic systems, and essential resources such as energy and water.

Urban centers tend to have a high density of buildings, paved roads and parking lots—all of which absorb and retain heat. Green spaces such as parks and golf courses, in contrast, reduce heat levels in neighborhoods by lowering surface and air temperatures through evapotranspiration. Mature trees and other natural features provide shade, deflect the sun's radiation and release moisture into the atmosphere. As heat waves become more frequent and intense, cities are experiencing higher nighttime and mean temperatures compared with areas that have a lot of green space. This is commonly called the heat island effect.

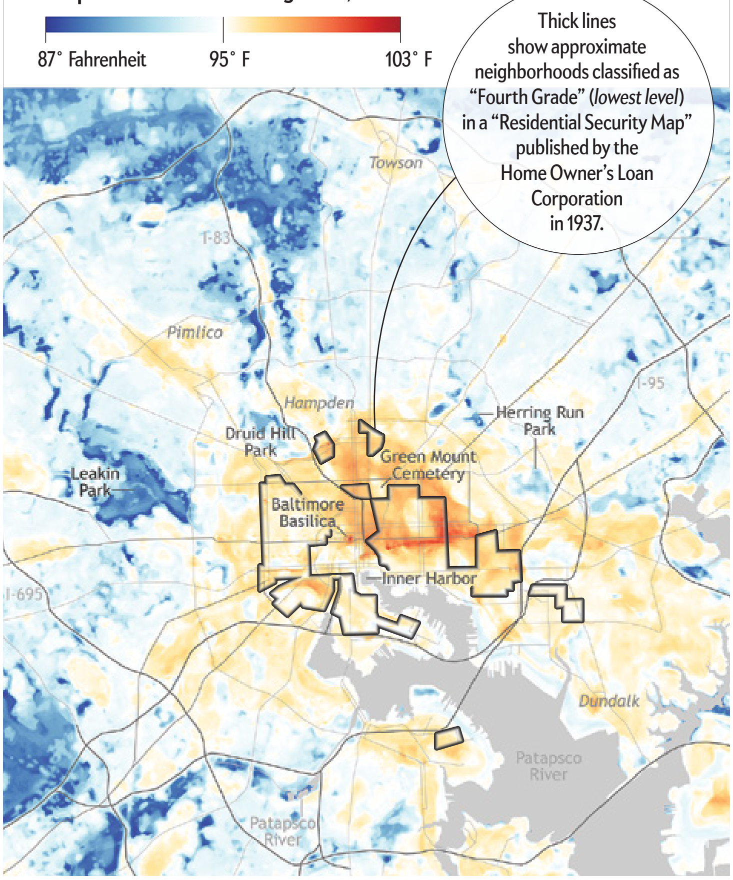
Within these heat islands are especially hot hotspots, or intraurban heat islands, which tend to have the least green space. Recent studies have shown that "extreme

Graphics by Jen Christiansen

Overlap between Heat and Historically Redlined Neighborhoods

Within a single city such as Baltimore (*shown here*), urban heat island effects can vary greatly based on hyperlocal infrastructure. This heat map shows temperatures collected by citizen scientists across the city at 3 P.M. on August 29, 2018. The outlined zones are historically redlined neighborhoods, where discriminatory policies led to poor urban planning. They overlap with some of today's extreme hotspots.

Temperature at 3 P.M. on August 29, 2018



Sources: NOAA Climate.gov (*map*); Portland State SUPR Lab (*data*); Redlined zones added by Jen Christiansen using Residential Security Map of Baltimore Md., prepared by Home Owner's Loan Corporation Division of Research & Statistics, with cooperation of the Appraisal Department, May 29, 1937, courtesy Baltimore City Sheet Maps Collection, The Sheridan Libraries, Johns Hopkins University, https://jhir.library.jhu.edu/handle/1774.2/32621 (*reference for redlined zones*)

heat exposure is highly unequal and severely impacts the urban poor," as stated in a 2021 paper in the *Proceedings of the National Academy of Sciences USA*. The link between vulnerable populations and the lack of green space in the neighborhoods where they live results from cascading issues; among them are policies designed to restrict the upward mobility of certain groups, such as redlining practices that date back to the 1930s.

The term "redlining" denotes the assignment of grades to residential areas based on their racial composition; the lower-graded neighborhoods were less likely to receive investments, and people living in them had a harder time obtaining loans. The redlining practice grew from President Franklin D. Roosevelt's federally funded New Deal, which enforced segregation practices. The Federal Housing Administration, for instance, refused to insure the homes of Black and other nonwhite families or homes owned by white people that were considered too close to Black neighborhoods. Local governments that practiced "benign neglect" created isolated zones devoid of resources and opportunities.

Today's hotspot communities often suffer from the long-term effects of these discriminatory urban-planning policies, including inadequate access to parks and green spaces. And for people who live in these areas, central air-conditioning may not be an affordable solution, if it's even an available option. Many older buildings have never been retrofitted to accommodate central air—a common situation in the inner city in places such as New York, Detroit and Baltimore—leaving people reliant on smaller, portable window units and fans.

Regardless of the cooling technology used, low-income households in America spend 8.1 percent of their income on energy costs compared with 2.3 percent for non-low-income households, according to a 2020 report from the American Council for an Energy Efficient Economy. The ability to reduce energy costs (by updating house insulation and switching to efficient electric appliances, for instance) is largely out of the control of renters and may be unaffordable for lower-income homeowners. Thus, the most vulnerable people in the hottest hot zones must face decisions that pit the high energy cost of staying cool and safe against providing for other necessities of life. As a result, they may be more at risk for heat-related illness and death because of both overexposure to high temperatures where they live and the lack of resources to mitigate the effects of that heat.

BETTER RISK ASSESSMENT

IN THE PAST the heat island effect had little connection to global climate trends, but recent research findings suggest that, on average, urban heat island warming will be equivalent to about half the warming caused by greenhouse gas emissions by the year 2050. In other words, cities get a double punch: both climate change and urban development that swaps green space for pavement are warming metropolitan areas, influencing the chemistry of the atmosphere and intensifying urban air pollution. Currently global temperatures are predicted to increase by 3.8 to 6.3 degrees F by 2100—resulting in intolerable heat thresholds for urban environments.

Given the scope of the problem, how can we lessen the negative effects of extreme heat events on historically vulnerable urban communities? At Howard University's NOAA Cooperative Science Center for Atmospheric Sciences and Meteorology, my colleagues and I are interested in understanding how people process risk associated with extreme heat and respond to heat advisories. As scholars from disciplines spanning atmospheric sciences, communications, computer science and sociology, we want to learn how to inform better decision-making in communities so we can help them make useful and realistic plans for both the short and the long term.

Our current work is taking place in Baltimore, which ranks among the U.S. cities with the most intense urban heat island effects. A 2020 study led by Jeremy Hoffman of the Center for Environmental Studies at Virginia Commonwealth University showed that in Baltimore neighborhoods where a history of redlining practices has blocked investment, summer temperatures are nearly six degrees F hotter than the citywide average. The research project uses an integrative citizen science approach, giving us an excellent opportunity to learn from members of communities experiencing some of the worst effects. To assess people's responses to weather forecasts and heat events in Baltimore, we developed an app that merges weather data, risk communication and behavioral health information to push messages to study participants. The app also collects behavioral responses to extreme heat alerts.

Some early research activities involved talking with city residents to discern how they perceive and respond to extreme heat events. As part of this, we asked about their awareness of warnings and potential impacts of exposure. We conducted interaction-based interviews with focus groups, which allowed us to observe conversations among participants and hear both individual and collective responses.

When asked about their level of awareness concerning heat advisories, many focus group participants appeared to have general knowledge about the topic: they reported being aware of heat advisory warnings, and the majority said they modified their behavior in response to those warnings by trying to drink more water and delaying physical activities until later in the day. Most people, however, were unsure of the meanings behind the different threat levels, which are typically presented as part of a weather forecast, and were confused about how to interpret them. For instance, some people were not aware of the difference between a heat "watch" (be prepared) and a heat "warning" (take action now to protect yourself).

We also found that people have very limited knowledge of the "heat index"—a measure that factors in relative humidity to estimate how a given day's temperature actually *feels* to the human body. This data point is superior to temperature alone for alerting the public to especially dangerous types of heat. It became clear to us that people would additionally benefit from greater awareness of the effects of climate change in general, so they would know to expect heat-related problems to get worse over time.

One of our essential findings is that knowledge of general heat risks does not necessarily lead to an accurate perception of one's own risk. Several study participants indicated that they were aware of the different ways people could protect themselves from heat, but this knowledge did not translate into their *personally* taking protective actions. Some participants said they do not believe they are at direct risk. As one person put it: "To me, it being 90 degrees did not really say anything [because I'm] from the Caribbean. Like, sometimes it is 100, 105." Interestingly, our study's older participants, considered by health professionals as high risk for the dangerous effects of heat exposure, did not think of themselves as especially at risk.

This summer the Howard University team is distributing air monitors, Internet hotspots and cell phones (for those who do not currently own one) to community members who elected to participate in the study. These tools will collect data at no cost to the participants, who will receive $200 for taking part in the project over three months. The real-time indoor weather data will enable us to monitor heat exposure. As temperatures rise, the study participants will be alerted to the onset of an extreme heat event or heat wave via an app or, when appropriate, phone calls and e-mail. They will be reminded to use the app to access information on the heat index, as well as the risk of extreme heat exposure and suggested protective actions. The types of help and resources recommended by the app will be personalized for the study participants based on their individual risk factors.

Subsequent alerts will be tailored to the needs of the target population, with particular attention to message framing. This approach will include a clear and easy-to-digest explanation of the levels of risk uncertainty to help people understand why they should take action even if some parts of the forecast don't come to fruition. We think people need more information to best manage their expectations, not just to make good decisions. It's important for them to do so because the National Weather Service is increasingly incorporating the language and visuals of uncertainty into public discussions that reflect the estimates in forecast models. After data have been collected, study participants will be surveyed for insights on how the messaging influenced their self-protective actions and help-seeking behaviors.

Although there is no fail-safe approach to addressing the risks associated with high heat exposure, talking more about what's at stake is a good start. The potential dangers of excessive heat extend beyond physiological health to facets of life such as increased rates of domestic violence and crime. There are economic consequences, too: according to the Atlantic Council, the U.S. could lose some $100 billion annually because of extreme heat effects.

The hope is that increased awareness of the gap between risk and protective actions will force policy makers to take these issues more seriously and factor them into climate-preparedness plans. Opening cooling centers during a heat wave might not be enough to prevent unnecessary deaths if people don't think they need to go. More effective communication is one critical tool for reducing the harmful consequences of extreme heat on human health. SA

FROM OUR ARCHIVES

Why Extreme Heat Is So Deadly. Tanya Lewis; ScientificAmerican.com, July 22, 2021.

scientificamerican.com/magazine/sa

WEATHER

THE NEW TORNADO ALLEY

Tornado outbreaks are migrating eastward from Texas and Oklahoma toward Tennessee and Kentucky, where people may not be prepared

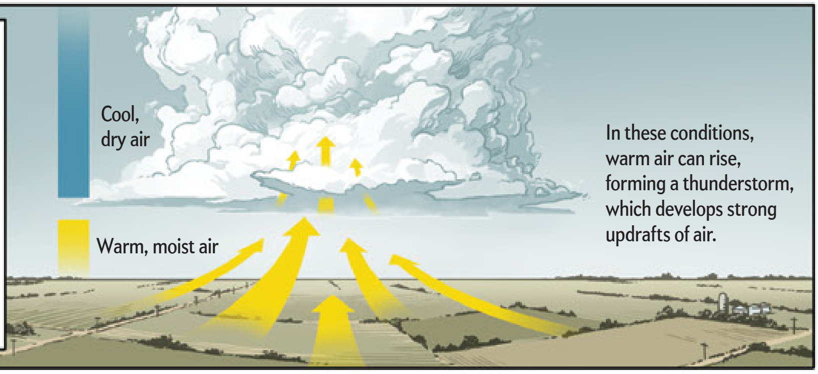
By Mark Fischetti
Graphic by Matthew Twombly
Map by Daniel P. Huffman

Roughly 1,200 tornadoes strike the U.S. during an average year. They're prevalent in the U.S.—far more so than anywhere else in the world—because its geography sets up the perfect conditions, especially in spring and summer. Westerly winds from the Pacific Ocean drop their moisture when they push up over the Rocky Mountains, becoming high, dry and cool as they move farther east. Similar winds may descend from Canada. Meanwhile low, warm, humid air streams northward from the Gulf of Mexico. Flat terrain along these paths allows the winds to move relatively uninterrupted, at contrasting altitudes, until they run into one another. The angles at which they collide tend to create unstable air and wind shear, two big factors that favor tornado formation. Although somewhat similar

Continued on page 74

How Tornadoes Form

Tornadoes are violent vortexes that can rip apart anything they encounter. They usually form when the atmosphere is unstable—when there is warm, moist air near the ground and cold, dry air high above and when winds are mixing.



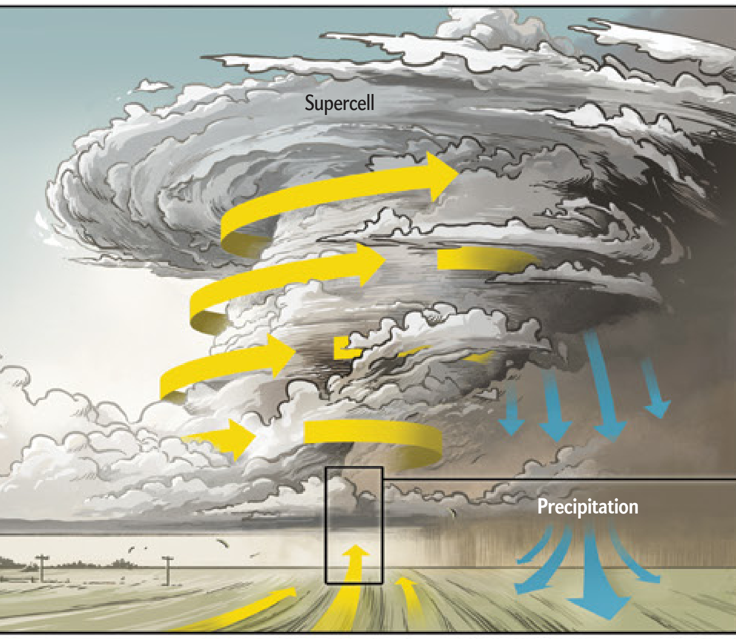
In these conditions, warm air can rise, forming a thunderstorm, which develops strong updrafts of air.

If winds are slow near the surface, fast high above and are blowing in different directions, creating what's known as vertical shear, they can form a tube of horizontally rotating air within the storm.

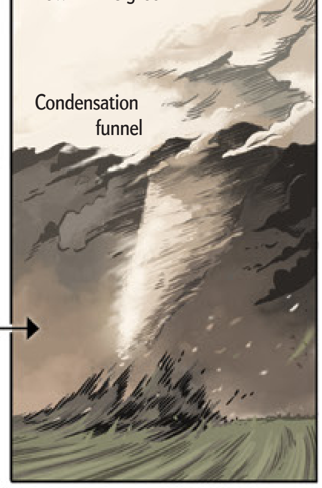
If updrafts remain strong they can bend the tube upward, turning it into a vertical condensation funnel that continues to rotate.

This storm system is called a supercell.

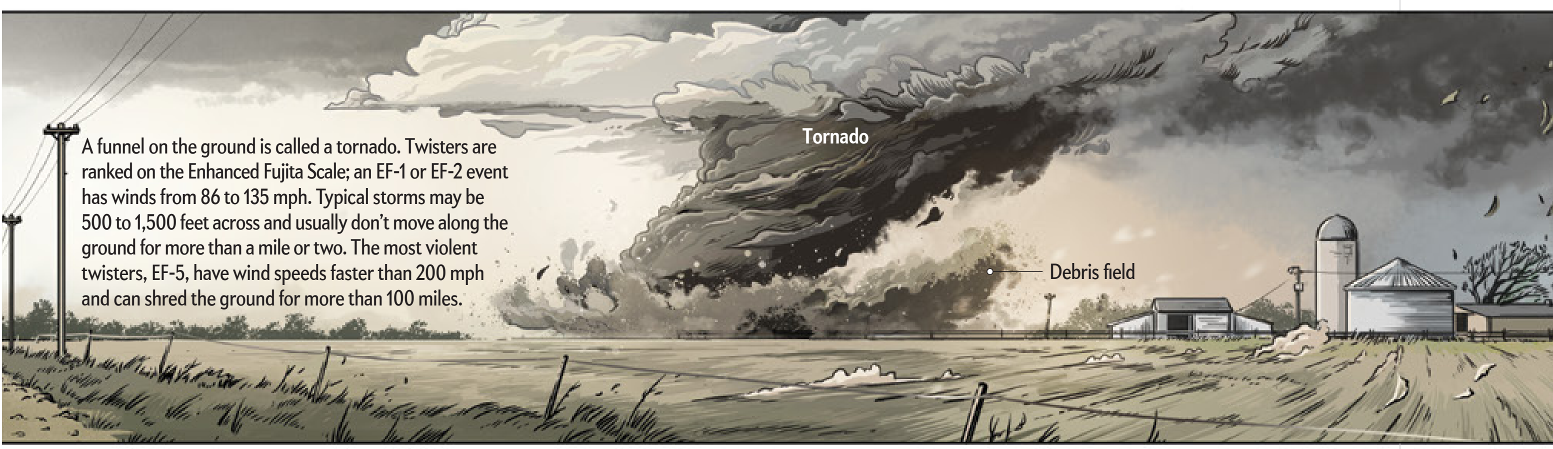
The supercell draws up even more warm, moist air, which intensifies the updrafts. Falling precipitation creates cooler downdrafts.



Cool downdrafts can make the funnel narrower and cause it to rotate faster. They also can draw a funnel at altitude down toward the ground.



A funnel on the ground is called a tornado. Twisters are ranked on the Enhanced Fujita Scale; an EF-1 or EF-2 event has winds from 86 to 135 mph. Typical storms may be 500 to 1,500 feet across and usually don't move along the ground for more than a mile or two. The most violent twisters, EF-5, have wind speeds faster than 200 mph and can shred the ground for more than 100 miles.



A TWISTER formed by a supercell nears its final stage, known as a “rope out” when it takes this shape.

Mitch Dobrowner

Continued from page 70

air masses do clash in other places, such as Uruguay and Bangladesh, the forces are much more powerful over the U.S. Canada ranks second worldwide with 100 twisters a year.

Although tornadoes touch down in many places across the eastern half of the country, from the 1950s through the 1990s they struck most often in Tornado Alley, an oval area centered on northeastern Texas and south-central Oklahoma. More recently, that focus has shifted eastward by 400 to 500 miles. In the past decade or so tornadoes have become prevalent in eastern Missouri and Arkansas, western Tennessee and Kentucky, and northern Mississippi and Alabama—a new region of concentrated storms.

Tornado activity in early 2023 epitomized the trend. A violent twister with wind speeds of 170 miles per hour struck Rolling Fork, Miss., on March 24, killing at least 26 people. A week later storms in the new tornado alley killed more than 30 people, and another group on April 4 damaged more than 80 structures in Bollinger County, Missouri. Those events happened in just the run-up to peak season in April and May.

Data gathered in the past two years show that in addition to solo storms, large tornado outbreaks—multiple twisters spawned by a single weather system—are shifting even more definitively to the east. The swarms are clustering in a tighter geographical area than in the old Tornado Alley, too. And outbreaks may be getting fiercer and more frequent. "It looks as if we may be having fewer days in the U.S. with just one tornado and more days when there are multiple tornadoes," says Naresh Devineni, an associate professor at City University of New York, who co-led a 2021 geographical analysis of large tornado outbreaks.

Why is this shift happening now? Most often tornadoes are created by a supercell—a strong thunderstorm with a rotating updraft of air. Supercells tend to form when warm, humid, low-level air interacts with cool, dry, upper-level air, and climate change is generating warmer, moister air. Tornadoes also are more likely to develop when the local atmosphere is unstable, "and warming increases instability," says Zuohao Cao, a tornado expert at Environment and Climate Change Canada, who co-led a recent study on storm touchdown locations. Climate change is warming the Gulf of Mexico as well, which can send generous amounts of water vapor into the southeastern U.S.

Research suggests that the so-called dry line is also shifting eastward. The imaginary line runs north from the U.S.-Mexico border up to Canada, dividing the wetter eastern U.S. from the drier western U.S. (To the east, thirsty crops such as corn predominate; to the west, drought-tolerant wheat prevails.) The line, which for centuries has fallen roughly along the 100th meridian, has moved east by about 140 miles since the late 1800s. The dry line "can be a boundary for convection—the rising of warm air and sinking of colder air that can fuel storms," wrote Ernest Agee, professor emeritus of atmospheric science at Purdue University, in the Conversation in 2022.

Climate change may extend the typical tornado season as well. Milder winters mean the unstable air masses that can create supercells may become more likely in March or even earlier in the southeastern U.S.

Tornado Alley moving eastward is more than a meteorological curiosity. The shift is serious: Tornado shelters are common in Texas and Oklahoma but less so elsewhere. The Southeast is more densely populated, and mobile homes, which fare poorly in windstorms, are much more common. Tornadoes in the Southeast also occur at night more often than they do farther west, in part because winds can bring ample moisture from the Gulf after dark. Studies show that tornadoes that strike at night are 2.5 times more likely to cause fatalities.

Local and state governments in the new bull's-eye region might want to improve community shelters and warning systems, strengthen building codes, better equip emergency responders, and educate residents about what to do—and not to do—if a tornado is headed their way. SA

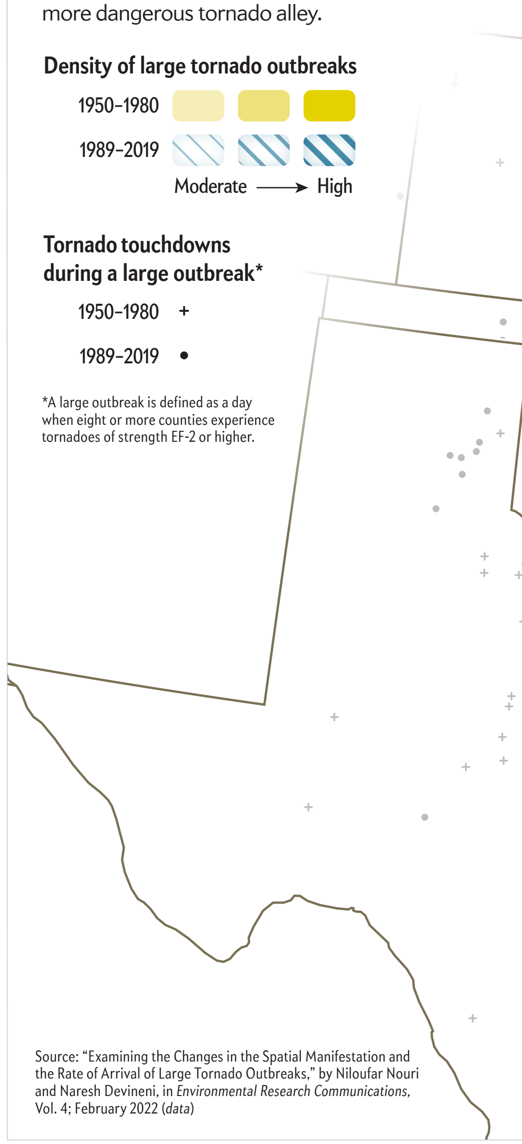
FROM OUR ARCHIVES

Building a Weather-Smart Grid. Peter Fairley; July 2018.

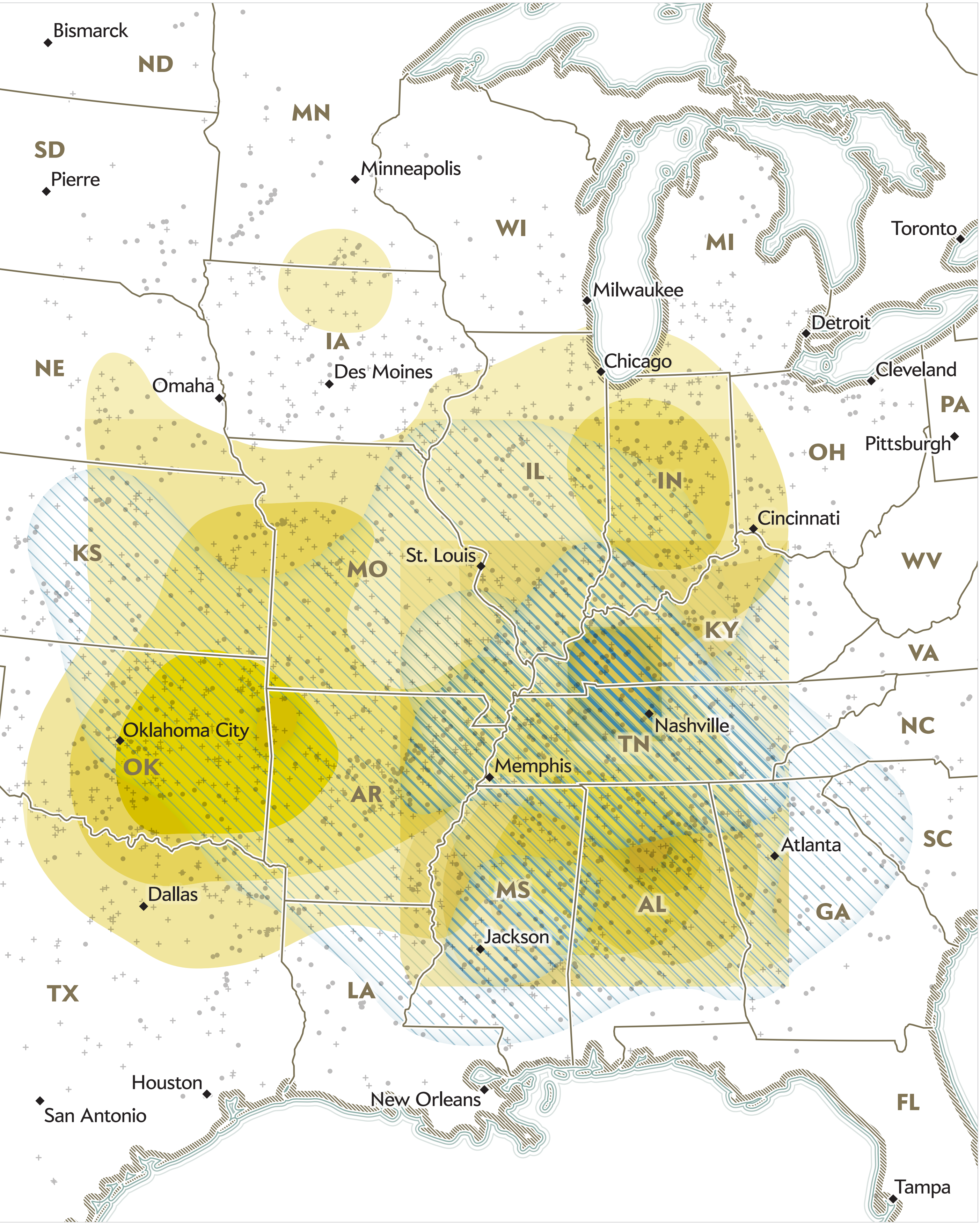
scientificamerican.com/magazine/sa

Tornado Alley Shifts Eastward

Large tornado outbreaks—when numerous twisters touch down in the same region on the same day—are happening more frequently in the U.S. From 1950 to 1980, large outbreaks occurred most often in a roughly oval-shaped region encompassing northeastern Texas, eastern Oklahoma, and western Arkansas and Missouri (*darker yellow contours*). Between 1989 and 2019, the locus shifted eastward, covering western Kentucky and Tennessee plus northern Mississippi and Alabama (*darker blue contours*). The area experiencing the highest concentration (*darkest yellow and blue*) has also gotten smaller—an even more dangerous tornado alley.



Source: "Examining the Changes in the Spatial Manifestation and the Rate of Arrival of Large Tornado Outbreaks," by Niloufar Nouri and Naresh Devineni, in *Environmental Research Communications*, Vol. 4; February 2022 (*data*)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CLUES, CONTROVERSIES AND COVID ORIGINS

Animals and the COVID-causing virus both were at a market in China in early 2020. Could that have started the pandemic?

By Tanya Lewis

Illustration by Ellen Weinstein

Tanya Lewis is a senior editor covering health and medicine for *Scientific American.*

THE RACCOON DOG DOES NOT LOOK PARTICULARLY THREATENING. THE SMALL MAMMAL resembles those familiar masked trash bandits that inspired its name, although it is most closely related to foxes. Raccoon dogs are native to the forests of eastern Asia, and the furry omnivores eat rodents, insects, crustaceans and plants. In China, they are commonly sold for their meat and fur. But recently the creature has become embroiled in the tense debate over the origin of the virus that causes COVID.

Genetic evidence collected by Chinese researchers in January 2020—and finally made public earlier this year—puts raccoon dogs and other wild animals at a market in Wuhan, China, that was the epicenter of many of the earliest human COVID cases. That same evidence puts the COVID-causing virus, SARS-CoV-2, in many of those same market stalls. Experiments have shown raccoon dogs can be infected with and transmit SARS-CoV-2. Taken together, many scientists say, these findings point to a scenario in which the virus jumped to people at the market. But other researchers emphasize this is only circumstantial evidence—although they agree it warrants further investigation—and still leaves open the possibility of a "lab leak" as the start of the pandemic.

There is no video footage of an infected raccoon dog sneezing on a human and giving them the virus. Even if slam-dunk epidemiological evidence exists, Chinese authorities have not been forthcoming about it. But finding a susceptible animal at the same place and around the same time that the first people caught COVID may be some of the best evidence we'll get, says Alex Crits-Christoph, a senior scientist in computational biology at Cultivarium, a nonprofit microbiology research organization.

This twist to the origins search began in early March, when scientists at the Chinese Center for Disease Control and Prevention (CCDC) and their colleagues uploaded genetic data from swabs taken at the Huanan Seafood Wholesale Market to a scientific database. An international team of researchers led by Crits-Christoph found the overlapping genetic material of animals and the virus at the same spots in the market, a connection the Chinese researchers soon confirmed with their own analysis in *Nature.*

The proximity is key, says Angela Rasmussen, a virologist at the Vaccine and Infectious Disease Organization–International Vaccine Center in Saskatchewan and one of the collaborators on the international report. "It's not a 'smoking raccoon dog,' but it is pretty indicative that in exactly the same part of the market that our other analyses suggested we would find the animals, now we found them in that exact spot—with the virus and without, importantly, much human [DNA present]," Rasmussen says. The findings confirm previous reports that live animals were sold at that market, and evolutionary biologist Edward Holmes of the University of Sydney—a co-author of the international team's report—had photographed live raccoon dogs there several years earlier.

What the swab results don't do is confirm that the raccoon dogs or other animals were actually infected

RACCOON DOGS (*Nyctereutes procyonoides*) may have transmitted the COVID-causing virus to people, according to a recent genetic analysis.

prill/Getty Images

with the virus or that they were the animals that first spread it to people. The leading alternative scenario is that the virus leaked from one of several virology labs in Wuhan that conduct research on coronaviruses. And although there is no direct evidence for this or other theories, the new data cannot rule them out.

Such lingering uncertainty isn't unusual: tracing the origin of a new viral disease can take decades. For instance, masked palm civets sold at an animal market in Guangdong, China, were identified as an intermediate host of the SARS virus that caused an epidemic in 2002–2003, but it took another 15 years to trace the source of the virus to bats; the origin of the Ebola virus, as well as those of many other viruses, has never been found. With SARS-CoV-2, the Chinese government's reticence to release all the data it has collected has hampered the origins search—for example, the CCDC team first released a preprint of the market data in 2022, two years after collecting them, and they didn't label the animal species present.

Many of the virus-positive samples were clustered in the market's southwestern corner, in the same place where stalls selling live animals were previously reported. Half a dozen virus-positive samples were also positive for raccoon dog DNA or RNA, often at higher amounts than human genetic material. One sample, known as Q61, contained a lot of raccoon dog material but very little human material. The report's authors also found genetic material from Amur hedgehogs, Malayan porcupines, masked palm civets, Siberian weasels, hoary bamboo rats, and other animals. Any of these species may have served as an intermediate host of the virus, which scientists believe likely originated in wild bats. Most of these other animals, however, have not been shown to be susceptible to SARS-CoV-2. Raccoon dogs have.

"This is not conclusive evidence that an animal was infected, but it's very consistent with that," Crits-Christoph says. If the market were not the place where SARS-CoV-2 crossed from animals into people but instead the site of a superspreader event caused by people who were already infected, "you'd have to ask, Why there?" Crits-Christoph says. "If humans brought it there, why did they bring it to the place in Wuhan with the most stalls selling wild animals?"

Although the CCDC study in *Nature* confirms the genetic identification of animals sold at the market, it doesn't draw the same conclusions about their role. Instead the authors write that "these environmental samples cannot prove that the animals were infected." And even if animals did carry the virus at the time of the market sampling, the CCDC research-

IN WUHAN, the Huanan Seafood Wholesale Market was the site of many early COVID cases.

Noel Celis/AFP via Getty Images

ers add, it is quite possible they picked it up from people—not the other way around.

The international team's animal findings, however, build on previous studies supporting the market as an early epicenter of SARS-CoV-2 and suggesting multiple zoonotic origins linked to the market. One earlier research project was led by Jonathan Pekar, a doctoral student in biomedical informatics at the University of California, San Diego, and a co-author of the newer report on the market swabs. Pekar's group proposed that there were two lineages of the virus—A and B—circulating in Wuhan in the earliest days of the pandemic and that both were connected to the market. The B lineage is the first one believed to have infected humans. If the virus first jumped into people at the Wuhan Institute of Virology, as some people believe, researchers would have had to introduce it to the market twice, Rasmussen says.

"Is it possible that somebody working in the lab could have gotten infected with lineage B, showed up at the market and didn't infect anybody else on their way there, even though it's [about 10 miles away]—-and then the next week the exact same thing happened with lineage A virus?" Rasmussen says. "It's possible, but I don't think it's very plausible, compared to the alternative: that lineage A and lineage B came from the animals, and then there were two separate spillovers."

But the two-lineage interpretation has its critics. They have pointed out that these lineages differ by only two genetic mutations. Given how rapidly SARS-CoV-2 evolves, it is possible that one lineage evolved into the other *after* people brought it to the market, rather than requiring two separate human introduction events. "I don't think that the fact that, among the early viruses, they can be split into these two groups that differ by just two mutations really means that there had to be two introductions," says Jesse Bloom, a computational biologist at the Fred Hutchinson Cancer Center in Seattle, who has studied the evolution of the virus. "It's also possible that one could have evolved into the other in humans."

The animal evidence from the swabs does give scientists a better idea of where to look next for animals closer to the origin of the virus, Crits-Christoph says. Researchers can now focus their efforts upstream of the market, in the wildlife trade or on farms where these animals may have been bred. If a genetic sequence of the virus could be extracted from such an animal, Crits-Christoph says, it may be possible to tell whether a progenitor of the pandemic virus had been evolving in an animal host.

But these newer findings from the market don't quite fit the time line of the pandemic, a problem that researchers critical of the wildlife spillover theory are quick to point out. The samples were taken nearly a month after symptoms appeared in the first confirmed COVID cases, around December 10, 2019—and evolutionary genetic analyses suggest the virus began circulating in humans as early as mid-November of that year. It's impossible to know if the same animals were at the market then or whether they had been infected prior to the first human cases. "I think the major limitation is that, unfortunately, the sampling was being done in January 2020," not the beginning of December 2019, Bloom says. "It's difficult to interpret what the correspondence between the animal and human content of these samples and the SARS-CoV-2 content means."

Bloom released a preprint of his own analysis of the CCDC's data in late April 2023. It confirmed the presence of numerous animals at the market, including raccoon dogs. But Bloom went on to quantify the amount of DNA from different animals, and unlike Crits-Christoph's team, he included all animals with spinal cords (chordates), not just mammals. SARS-CoV-2 is only known to affect mammals, but Bloom included chordates as a control group. According to his analysis, very few of the SARS-CoV-2-positive samples contained a significant amount of raccoon dog DNA. In fact, the samples that contained the most virus also had the most genetic material from fish, which are not thought to be susceptible to the virus.

"What I take this to mean overall is that the genetic content of these samples—and the SARS-CoV-2 content of these samples—suggests that you can't really use that type of analysis to figure out if any animals were infected," Bloom says. "It does not prove that animals were never infected; it just indicates that from these samples, you can't really conclude anything, because the type of signal you're looking for, you see it in things that clearly don't make any sense at all."

Crits-Christoph does not buy that objection. He points out that correlations are not an appropriate way to answer the question of which specific animal shed the virus. The virus found in stalls selling seafood was almost certainly shed by sick humans. Of course, Crits-Christoph's own analysis is also based on a correlation: SARS-CoV-2-susceptible animals and parts of the market with positive virus samples. The difference, he says, is that he was merely using the correlation to show that the animals were there, not that any specific animal was infected at the time.

Alina Chan, a scientific adviser at the Broad Institute of the Massachusetts Institute of Technology and Harvard University, who has been an outspoken advocate of the lab leak hypothesis, has her own objections to the market stall data. The animal genetic sequences simply confirm there were animals at the Wuhan market, something that was already known, she says. "To me, it's not shocking that you would find raccoon dog material on these surfaces," Chan says. She notes that SARS-CoV-2 was found all over the market, not just at the animal stalls.

Bloom, however, points out that lab leak theories rely just as much on circumstantial evidence as natural origin theories do. The main argument for leaks, he says, is proximity-based: "The outbreak started in Wuhan, where there are labs that study SARS-like coronaviruses. There's definitely no direct evidence that any of the labs were studying a virus identical to SARS-CoV-2."

There are, Bloom thinks, four plausible scenarios by which the pandemic could have started. Two of them relate to a lab or a researcher: A scientist from one of the Wuhan Institute of Virology labs got infected by a bat while doing fieldwork, or a scientist at one of the labs collected a virus sample from a bat or other animal, brought the sample back to Wuhan and became infected while working with it in the lab. The other two scenarios involve natural spillover: A raccoon dog or other intermediate animal host directly infected a human in Wuhan or elsewhere, or a bat directly infected a person outside Wuhan, who then brought the virus back to the city (the bats that carry similar viruses aren't found in Wuhan). "In my mind, honestly, all these things sort of remain possible," Bloom says. All these scenarios "are sufficiently worrying that we should try to mitigate them."

Chan adds what she claims is another possible scenario for a lab-related origin: that the virus had been brought to a lab and, in an attempt to learn about how it mutates, was engineered to better infect human cells—and somehow got out into the world. This notion is highly controversial, and many scientists note that there is really no evidence for it. Chan and others have pointed to an unusual feature of the virus called a furin cleavage site as an indication that it was engineered. But such sites have also been found in other coronaviruses in nature, so this idea hasn't convinced many virologists and infectious disease specialists.

At least eight U.S. intelligence agencies have conducted their own investigations of the virus's origins. Four agencies concluded with "low confidence" that a natural spillover from animals is most likely, two favor a lab leak with "low" or "moderate" confidence, and two are undecided. The U.S. government has ordered information related to COVID origins to be declassified.

A firm answer to the origins puzzle has been elusive, but a hard puzzle is not an impossible one, Crits-Christoph says. He thinks scientists will keep getting closer. "People keep betting that no new information will come out, and new information keeps coming out," he adds. "I would never make that bet. We're going to know more." SA

FROM OUR ARCHIVES

Why We Don't Know the Animal Origins of the Coronavirus. Christine K. Johnson; ScientificAmerican.com, June 9, 2021.

scientificamerican.com/magazine/sa

COCKTAIL ICE comes in many shapes and sizes—and requires a lot of water and energy to make.

Shake, Chill, Froth, Dilute, Discard

Two hundred years ago the ice trade launched America's cocktail culture. Today a craft concoction might be the least sustainable item on the menu

By Amy Brady

Photographs by Lendon Flanagan

Amy Brady is executive director of *Orion* magazine and a contributing editor at *Scientific American.* She is author of *Ice: From Mixed Drinks to Skating Rinks—A Cool History of a Hot Commodity* (G. P. Putnam's Sons, 2023).

IN THE EARLY 19TH CENTURY, MORE THAN 100 YEARS BEFORE ELECTRIC REFRIGERATION, an entrepreneurial Bostonian named Frederic Tudor landed on an idea: He'd cut blocks of ice from his Massachusetts lake and sell it to places where temperatures were too warm for ice to form naturally. Potential financiers thought this plan was too absurd to work. How would he ship the ice without it melting, they wondered, and who would buy it when it could be harvested for free?

Ultimately Tudor not only succeeded at distributing and selling ice—his trade revolutionized how Americans thought of food. Having access to ice enabled people to better preserve their meat and milk, reducing instances of food poisoning and launching the concept of leftovers. The initial desire for ice in warm places, however, wasn't driven by solutions to spoilage and illness: it came from bartenders. Tudor sailed to Cuba in 1815, where he found his first receptive market in the country's ubiquitous café culture. Cubans trusted their local baristas, each of whom had their own twist on café Cubano or a proprietary recipe for mixing crushed fruit with rum. Tudor demonstrated how to adapt those drinks into iced versions, and any initial suspicion of frozen-water chunks floating in glasses quickly turned into frothy demand. Five years later, when Tudor introduced ice to the bartenders in New Orleans's French Quarter, the alluring taste of chilled alcohol gave birth to the American cocktail culture we have today.

Ice not only cools cocktails; it changes their flavor, texture and balance. Shaking liquids with one-inch cubes, for example, aerates the alcohol and emphasizes subtle flavors, and it can also produce thick foams necessary for drinks such as the whisky sour. Crushed ice, meanwhile, dilutes cocktails quickly because of its high surface area, creating the refreshing, slushy consistency found in juleps that would taste too cloying otherwise. Bartenders in New Orleans went from serving simple, lukewarm drinks to inventing some of the country's most famous cocktails. There was the Sazerac, of course, in which the ingredients are stirred with ice to temper the burn of the high-proof rye and absinthe while melding the flavors. Henry Charles Ramos created his eponymous gin fizz in 1888 by shaking the liquids (including egg white and citrus) with crushed ice for a full 12 minutes, "until there is not a bubble left but the drink is smooth and snowy white and the consistency of a good rich milk." In essence, ice transformed bartending from a mere job to a craft that involved creativity, chemistry and flourish.

Today even a moderately busy bar requires a lot of ice to get through a night. Bartenders are advised never to use the same cube twice when going through the steps of making a single cocktail: chilling glassware, shaking or stirring, and serving the drink. It's a process that requires a significant amount of water and energy. For years the hospitality industry has seen diners clamoring for foods that prioritize climate-friendly practices, such as local and seasonal ingredients that are grown or raised with carbon footprints in mind. Yet cocktail culture hasn't been hit with the same scrutiny. As the American West experiences water scarcity and energy prices remain volatile, the protocol for properly made cocktails doesn't look sustainable. Is it possible to make satisfying cocktails without so much ice?

ICE WAS, AND STILL IS, ONE OF THE MOST CRITICAL ELEMENTS in a cocktail. In *Liquid Intelligence: The Art and Science of the Perfect Cocktail,* food scientist Dave Arnold

Liza Jernow (*styling*); Okamoto Studio Custom Ice (*ice*) (*preceding pages*)

ICE was originally harvested in large blocks from frozen lakes, then shipped to areas with hotter climates.

Historic Collection/Alamy Stock Photo

explains how melting ice absorbs energy. In a cocktail, "there is no external heat source to supply the heat needed to melt ice, so the heat is drawn from the system itself," Arnold writes. "As a consequence, the entire system chills."

As any bartender will tell you, a cocktail flung back and forth over ice inside a shaker gets cold very fast. "The amount of energy you get from melting ice is phenomenal," Arnold told me. Calculator in hand, he explained that if you shake three and a half ounces of tempered ice for 12 seconds, you'll generate about 2,000 watts of power on average. This amount is roughly the maximum load that can be safely drawn from a typical American home's electric outlet. "There's no real other way to … extract that much heat from something as quickly," Arnold said.

How much ice does an average bar use? According to Todd Bell, senior energy analyst at energy-efficiency consulting group Frontier Energy, the amount "really depends on the operation." It might be between 200 and 300 pounds a night or far more.

"The ice-making procedure in bars is crazy wasteful," Arnold says. "It's kind of just built into the way [bars] operate things." Energy wasted from ice is largely because of in-house ice machines, which many—if not most—bars and restaurants use to maintain their steady ice supply. Ice machines run continually until they are full, potentially for several hours at a time. The machines vary widely in terms of the amount of energy they draw, however, depending on whether they are air- or water-cooled.

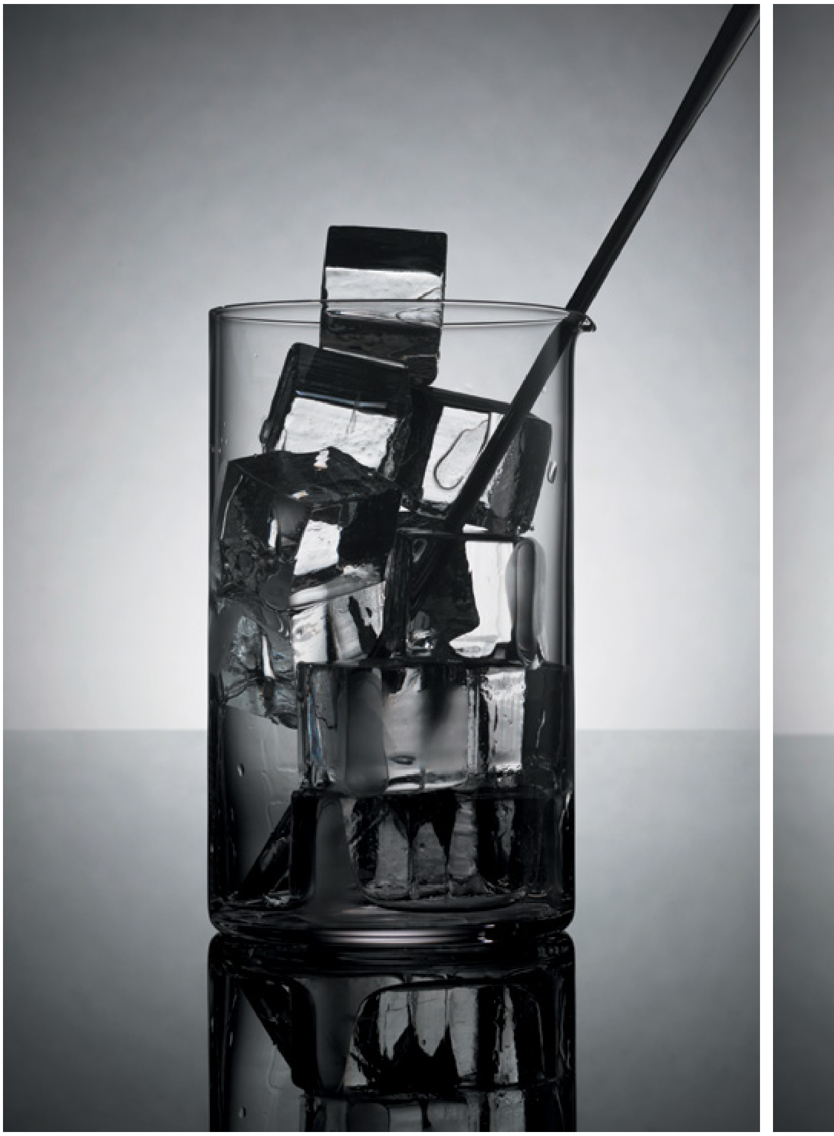
As the names suggest, air-cooled machines use air to transfer heat out of their systems, and water-cooled machines use water to do this. Well-maintained water-cooled machines are on average more energy efficient than those cooled by air, but they require much more water to produce ice. In nature, it takes only about 12 gallons of water to make 100 pounds of ice, Bell says. But water-cooled ice machines can require up to 100 gallons to produce 100 pounds, an amount so egregious that the U.S. Department of Energy's Federal Energy Management Program now restricts the installation of water-cooled ice machines except in buildings with cooling towers. Although air-cooled machines waste less water, many on the market still require more than 12 gallons of water to make 100 pounds of ice. In most cases, any unused water or ice at the end of the night is left to run down a drain.

MOST BARS AREN'T LIKELY TO GIVE UP ICE ALTOGETHER anytime soon. And cocktails aren't unsustainable just because of all the ice and water they require; they also tend to rely on ingredients that are shipped from far away, such as lemons and limes and liquors from around the world. But some bartenders are reimagining how ice and other ingredients can be used more sustainably. At Eve Bar in London, a new zero-waste menu includes cocktails made with leftover ingredients from its partner restaurant, Frog. The Bone Yard martini, for instance, uses vodka redistilled with venison bones to add a "bone marrow flavor" similar to what's found in some versions of the Bloody Mary. The technique is called a fat-wash because it lends the drink a savory flavor. "Whenever a dish [at Frog] changes, a cocktail [at Eve] changes," says Adam Handling, the chef and owner of Eve Bar.

To mitigate its waste, Eve Bar forgoes an ice-making machine for 55-pound blocks of ice, which are delivered to the bar by a local ice company. Eve's bartenders precut the block ice to "fit perfectly" in every type of glass used, he says, so that no ice gets wasted. For cocktails that traditionally call for the use of crushed ice, such as tiki drinks, the bar uses liquid nitrogen instead. "We don't use crushed ice at all," Handling says.

Jennifer Colliau is a sustainability-focused "cocktail nerd" who designed a bar menu that used as little ice as possible at The Perennial, a restaurant in San Francisco that closed in 2019. Colliau read about what Arnold has called the "science of shaking" and the "science of stirring" to devise ways to use less ice without affecting the taste and texture of cocktails. "Once you understand the role that dilution plays in drinks," she says, "you can control it in different ways." One method of eco-friendly cooling that she would never consider is whiskey stones, those small cube-shaped rocks made of soapstone or stainless steel that are sold as ice alternatives. "Whiskey stones are so stupid," she says. "You can make the stones cold, and you can put them in your whiskey, but [because they don't melt] there is so little thermal transfer of energy that your whiskey won't get cold."

To achieve dilution without ice, Colliau would measure a precise volume of water and add it to bottles of prebatched drinks that don't require fresh juice, such as martinis or manhattans. Juice will "oxidize over time," she says, and "start to taste nasty." This approach ensured consistency across her preassembled cocktails and eliminated the practice of throwing ice down the drain after shaking or stirring. Similarly, Re-, a bar in Sydney, Australia, serves most of its cocktail classics prediluted. "We never throw ice away," co-owner Matt Whiley says. The bar's machine is set to create only what's needed, "so it's empty at the end of



MAKING a cocktail requires lots of ice. A mixing glass (*left*) is filled with ice for diluting and chilling liquids; a rocks glass (*center*) is prechilled with ice water. All that ice will be dumped out and replaced with a fresh, large cube (*right*) to serve the drink.

the night," Whiley explains. Their drinks are made from food ingredients that tend to go to waste, including bread, dairy, bananas, rice and root vegetables. To serve those cocktails, Whiley uses ice carved from "off cuts"—slightly deformed blocks that his local ice-delivery company probably couldn't sell otherwise and would just let melt away.

When the same ice that is used to shake or stir a drink is used to serve the drink, it's called a "dirty dump," explains Camper English, author of *The Ice Book: Cool Cubes, Clear Spheres, and Other Chill Cocktail Crafts*. "It's not a common move," he says, because it can send bits of herbs or fruit into the drink, causing it to look "frothy, cloudier and chaotic in the glass." The move should also be avoided with any drink requiring fizzy liquids such as soda water because "smaller ice fragments provide more nucleation points that flatten the [liquid's] carbonation and block the surface of the cocktail," which prevents the tiny bubbles from rising out of the glass. But English actually prefers some drinks served this way, such as a mai tai or a margarita on the rocks, whose aesthetics and noncarbonated ingredients lend themselves well to the dirty dump technique.

Such resourceful approaches to bartending might signal the start of a shift—particularly for the U.S., where the ice trade was larger than anywhere else in the world. When Tudor launched his business more than 200 years ago, he probably never anticipated how consumed America would become with ice. Perhaps that's one reason ice is still somewhat rare in international cocktails. Consider the French Kir Royale, which consists of just black currant liqueur and champagne—it's almost always served neat. Or Hungary's Fröccs, which is made with soda water and wine and is "always served chilled" but "never over ice," according to *Afar* magazine. Drinks in this style—refreshing but not frigid; based in spirits, liqueurs or wines made from local fruits and herbs—could be front-runners in an energy-efficient, climate-conscious cocktail movement. SA

FROM OUR ARCHIVES

The Ice Trade. October 28, 1868.

scientificamerican.com/magazine/sa

An Elusive Brain Disorder

Medical compassion is essential for treating functional neurological disorders

By Z Paige L'Erario

Imagine your daughter has lost the ability to walk, and so you take her to the emergency room. How would you feel if you then overheard the doctor who saw your child laughing at her situation with colleagues? This scenario may sound absurd, but it's based on a true story.

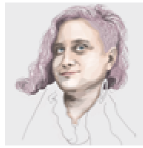
In 2021 researchers published several anecdotes from real cases involving functional neurological disorder (FND). What the vignettes reveal is that medical professionals, including nurses, ambulance drivers and physicians, sometimes treat this condition without concern, as though patients were simply faking their behavior. In my own experience as a neurologist, I have overheard doctors dismiss and laugh at their patients' FND symptoms when they are behind closed doors.

Although the disorder is not well known to the public, FND is actually one of the most common conditions that I and other neurologists encounter. In it, abnormal brain functioning causes physical symptoms to appear. FND comes in many forms, with symptoms that can include seizures, inability to move a limb and movement disorders. People may lose consciousness or their ability to move or walk, or they may experience abnormal tremors or tics. The ailment can be highly disabling and just as costly as neurological conditions with structural origins such as amyotrophic lateral sclerosis (also known as Lou Gehrig's disease), multiple sclerosis and Parkinson's disease.

Although men can develop FND, young to middle-aged women receive this diagnosis most frequently. During the first two years of the COVID pandemic, FND briefly made international headlines when vocal and motor tics such as repeating words or clapping uncontrollably spread with social media usage, particularly among adolescent girls.

So why would a medical professional accuse someone who has lost control of their limbs or has experienced a seizure of faking their symptoms? Unfortunately, many such professionals have a poor or outdated understanding of FND, despite the frequency with which they encounter it. Because nothing is structurally wrong with the patient's brain—clinical testing reveals no obvious injury—physicians may write symptoms off as "all in their head" or dismiss them as psychological. That response, recent research shows, can harm a person who is already suffer-

Illustration by Wenjia Tang



Z Paige L'Erario is a board-certified neurologist and transgender activist. They are currently a graduate student of social service at Fordham University and vice chair of the LGBTQI Section of the American Academy of Neurology.

ing. Fortunately, there is another path forward, rooted in sensitivity, respect and new evidence-based approaches.

Historically FND was called conversion disorder. The term came from the belief that traumatic stress was "converted" into functional neurological symptoms via psychological mechanisms. We now know that this understanding is incomplete. Stress and trauma *can* play a part. In fact, some researchers believe the unique global stressors our society faced during the COVID pandemic increased some people's susceptibility to the condition. But not every person with FND has experienced a traumatic event. New research suggests that biological susceptibility and exposure to stressful events over a lifetime may make a person more vulnerable to developing FND. In fact, relatively minor stressful events such as work-related stress, a viral infection or a small physical accident often precede the onset of FND symptoms.

Recent advances in brain imaging indicate that FND is caused by abnormalities in the functioning of brain networks. Some experts use the analogy that the brain's hardware (or structure) is fine, but the software (or processing) is malfunctioning. For example, studies suggest that in FND, several networks of electrical and chemical signaling pathways between groups of neurons or larger brain regions are not working together as typically expected. These networks include structures of the limbic system, such as the amygdala, that are important in our brain's processing of emotions or stress. Among people with FND, the amygdala is more active when subjected to sad or fearful stimuli. Other brain functions involved in FND include how we plan and interpret sensations in response to our movements, as well as our abilities to pay attention, be aware of our body and experience the feeling of control over our person.

Neuroimaging underscores that people with FND are not "faking" anything. Scientists have found decreased activity in supplementary motor areas and the right temporoparietal junction, which influence whether a patient's symptoms feel under their control. There are also abnormalities in the connections between brain areas responsible for interpreting internal physical sensations and motor planning. These differences in brain activity may help explain one key way that FND differs from other disorders that feature tics, such as the structural neurological condition Tourette's syndrome. As a research team at the University of Calgary in Canada explored in a paper published last November, people with Tourette's report some degree of control in suppressing their tics. In contrast, the symptoms of FND feel entirely involuntary.

Clinicians are also finding better ways to diagnose FND. In the past, neurologists considered conversion disorder to be a diagnosis of exclusion, meaning a diagnosis was made after physicians had ruled out structural neurological abnormality through examination, radiological imaging, laboratory studies and neurophysiological testing such as electroencephalography (EEG). As a result, many patients with FND felt their doctor had told them what they didn't have, not what they did have.

But in the past decade neurologists have developed diagnostic criteria to determine which symptoms are linked to functional brain abnormalities. These emphasize characteristic "positive," or "rule-in," findings based on a neurologist's physical examination, which can predict FND as the basis for a patient's symptoms. For example, a FND patient's symptoms may be inconsistent or change when distracted with another task. A combination of a thorough neurological examination, EEG, brain imaging and lab testing can show whether a person's symptoms are consistent with a structural brain pathology—for instance, a stroke or a brain tumor—or a functional condition such as FND.

Together these advances in the diagnosis and understanding of FND mean doctors are in a better position than ever to identify and understand this disorder. Nevertheless, many patients still have the disorienting, distressing experience of being treated with dismissal or disbelief by medical professionals.

This reaction has damaging consequences. In January a collaboration of researchers at the University of Sheffield in England, Arizona State University and the New York–based Northeast Regional Epilepsy Group laid out case studies and other evidence that clinicians' unsupportive responses to their patients may contribute to a sense of shame in people who are already suffering psychologically from their functional symptoms. In fact, being prone to shame may itself be an additional risk factor for FND.

This connection to shame and stigma takes on an even greater weight when we consider that marginalized groups such as members of the LGBTQ+ community may be at increased risk for functional disorders. A person experiencing stressors such as discrimination, bias and stigma because of their identity can internalize feelings of shame when their psychosocial support systems and coping mechanisms are inadequate or overwhelmed. If someone in this situation has FND, receiving treatment from a doctor who lacks empathy or a current understanding of the condition only makes things worse. Telling a patient their condition is "in their head" contributes to medical misinformation and further stigmatizes people with these disorders.

But this problem can be addressed. Researchers have found that how empathetically a doctor informs their patient about an FND diagnosis influences that patient's likelihood of accepting the diagnosis and successfully completing treatment. And appropriate treatment works. Therapy may combine psychoeducation, medication for any coexisting mental health conditions, psychotherapy and physiotherapy. Outcomes for people who receive sensitive and appropriate care are actually very good.

This year my colleagues and I will publish our observations on the treatment of LGBTQ+ people with FND. Our preliminary findings are promising. Most patients had improvement or complete resolution of their functional symptoms after treatment. In some of our patients, these results can be quite important. We have treated people with functional blindness who then regained the ability to see, and we have watched those in wheelchairs regain the ability to walk. In short, care and compassion can be powerful medicine. SA

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Our Sun Was Born Far, Far from Here

New clues suggest our nearest star has a complex origin story

By Phil Plait

Is the sun an only child? Or was it born into a (very, *very*) big family?

The answer would tell us more than just how awkward holiday family reunions can be (if you think yours are bad, imagine how much worse they would be with a few thousand sibling rivals). After all, the sun's origin story is, ultimately, our own. We've seen tremendous leaps in our understanding of how stars form, but, ironically, we still have some pretty fundamental questions about our nearest and dearest one—such as whether the sun was born solo or along with a huge passel of other stars.

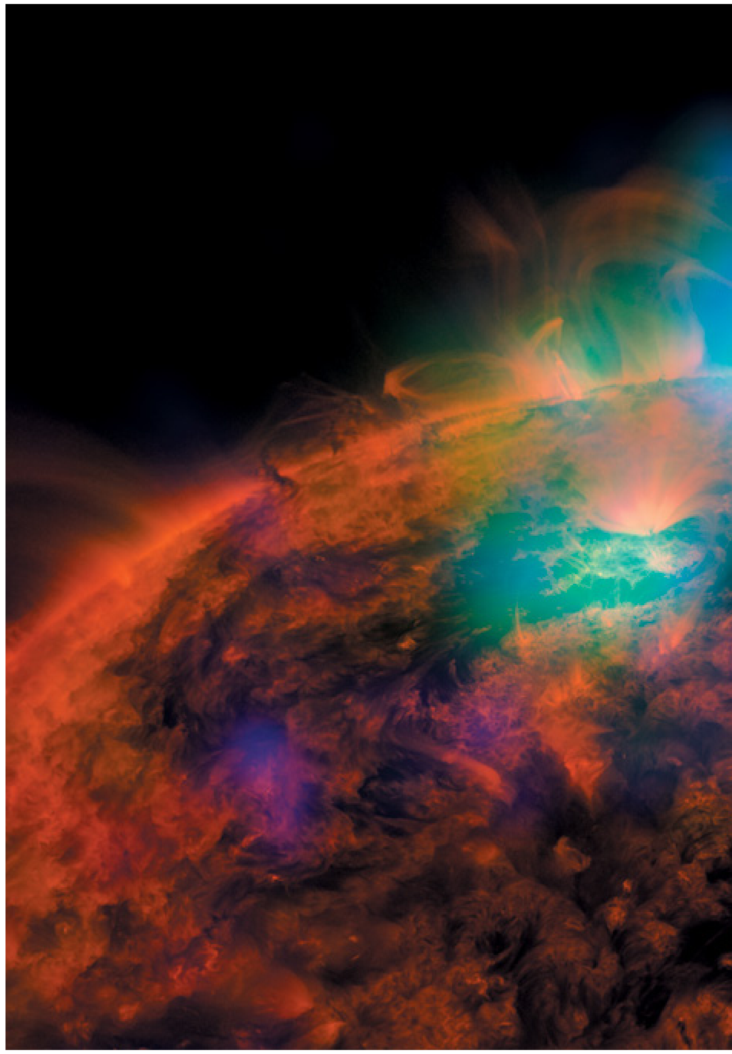
Despite the sun being close enough that we can almost touch it, the details of its inception have remained a mystery. The biggest problem is its age. Born 4.6 billion years ago, our star is well into midlife and has wandered far from its ancestral home—some nameless, now vanished "stellar nursery" of gas that long ago dispersed or consolidated into stars.

We can't find that nursery, but we can still learn about it. We have some evidence of it in the perhaps surprising form of meteorites, some of which still carry clues about their gestational environment during the birth of the solar system. For example, isotopes of elements such as potassium inside meteorites have told us where those objects formed in presolar cosmic clouds called nebulae, and variations between meteorites can be used to help determine a nebula's condition well before the emergence of any planets.

With data from meteorites in hand and aided by state-of-the-art computer simulations, an international team of astronomers investigated the likely natal environment of the sun. Its results were published in March in the *Monthly Notices of the Royal Astronomical Society*. Using a clever line of reasoning, the group suggests the sun not only had many siblings but was spawned in a rather metropolitan neighborhood.

Stars are born in nebulae when a cloud's interior collapses onto a central pilelike point that becomes the nascent star. Nebulae come in many shapes and sizes, from small, dark globules to immense molecular clouds. How a star forms in any given nebula is much more a story of nature than of nurture.

For example, the nebula Barnard 68 is a dark clot of cold gas and dust—tiny grains of silicates (rocky material) and complex carbon molecules similar to soot—relatively close to us in space at only a few hundred light-years away. It's one of my favorite objects: an eerie, pitch-black ghostly mass that utterly blocks light from stars behind it like an opaque hole in the sky.



A photograph shows our sun from data taken by NASA's Nuclear Spectroscopic Telescope Array (NuSTAR) and Solar Dynamics Observatory (SDO).

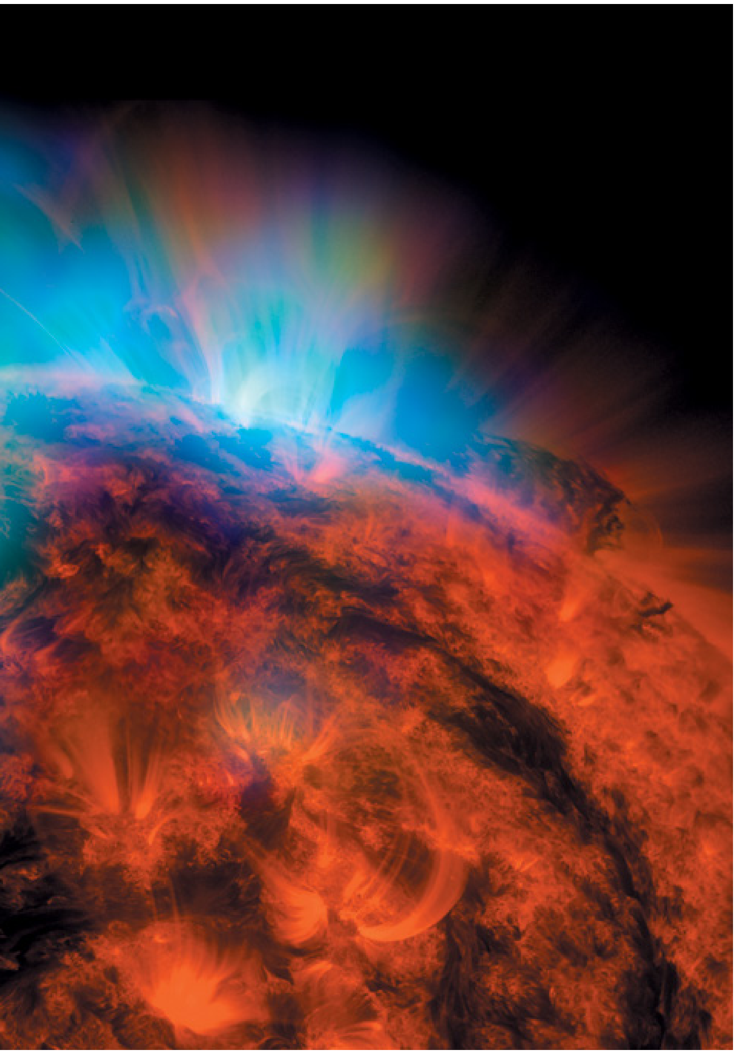
NASA/JPL-Caltech/GSFC

Only half a light-year across (just about three trillion miles), it has barely enough material in it to make a single star slightly heftier than the sun. Most likely it's in the middle of that process now and could transmogrify into a star in as little as 200,000 years.

On the other end of the scale we have the Orion molecular cloud complex, a truly enormous site of active star formation that's more than 1,000 light-years away and many hundreds of light-years across. It's beefy enough to make a staggering number of stars—at least 100,000 like the sun. The iconic Orion nebula, visible to the naked eye and the birthplace of hundreds of stars, is only one small part of this gigantic stellar factory.

Giant clouds like Orion are relatively rare but crank out

Phil Plait is a professional astronomer and science communicator in Colorado. He writes the *Bad Astronomy Newsletter.* Follow him on Twitter @BadAstronomer



stars on an industrial scale, whereas the smaller clouds are less fecund but litter the galaxy. It's not possible to discern the origin of the sun just by looking at these statistics, though; it could have come from either kind of stellar nursery.

These nebular environments are vastly different, which affects the stars they create. Massive stars found in a nebula have a big influence on their gestating siblings. They can blast out fierce winds of subatomic particles—like the solar wind but ramped up way past 11. These winds can seed forming stars with heavy elements such as aluminum and magnesium. Later, when they explode as supernovae, they fling a different mix of elements such as iron and cobalt a very long way.

Massive stars, however, are rare. Maybe one out of 100 stars is big enough to hold this kind of sway, and small nebulae simply don't make them. That means that in principle, looking at the chemical composition of the early solar system could tell us in what kind of nursery the sun was born.

This idea was the focus of the international team's recent research. The astronomers looked at two elements in particular: aluminum 26 and iron 60. Aluminum 26 is created inside massive stars and blown out in their winds, whereas iron 60 is forged in the thermonuclear hell of an exploding star. Both elements are radioactive, decaying into magnesium and cobalt, respectively. By carefully measuring the amounts of their daughter elements in pristine samples from the earliest days of the solar system—from meteorites, that is—we can learn about the environment in which the sun formed.

For their analysis, the scientists used the physics of nebulae and star formation to simulate a sunlike star's birth in a variety of environments, from nebulae containing very few stars (representing smaller clouds) to large ones with many thousands. Next they calculated the elemental composition of the proxy proto-presolar disk that emerged in each one and compared these virtual yields with what's actually measured in meteorites.

It's probable that the sun was more of a downtown city kid than a rural small-town star. Of course, with its nebular nursery gone, we can't confirm this hypothesis easily.

Their results indicate that as it formed in its natal disk, the early sun was probably pummeled by powerful winds and supernovae explosions—both arising from massive stars. That means the solar nursery was more like the Orion complex than Barnard 68.

By coincidence, in late 2022 a different team of scientists published a paper in the journal *Astronomy & Astrophysics* investigating a similar question. The researchers reason that at least one supernova must have exploded near the still-forming solar system to create the radioactive elements seen in ancient meteorites, so—because of the relative rarity of such events—they conclude the sun's birth cluster must have been very large to ensure, statistically, that this could occur.

In other words, it's probable that the sun was more of a downtown city kid than a rural small-town star. Of course, with its nebular nursery gone, we can't confirm this hypothesis easily. After all, you can't go home again.

And what of the sun's siblings—the thousands of other stars in its extended family? They once nestled together like a litter of puppies but wandered out on their own eons ago and are now orphans scattered across the galaxy. Still, astronomers do look for stars with the same age and composition as ours so we can discover more about our sun.

A reunion is pretty unlikely. So if we want to see a family album, we'll just have to put it together ourselves. SA

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NONFICTION

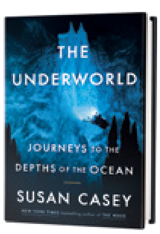
Exploring, and Exploiting, the Ocean's Depths

A new history of the deep sea—and the forces that threaten it

Review by Ben Goldfarb

The first bathysphere made its initial descent off an island in Bermuda on June 6, 1930, lowered into the Atlantic Ocean by a shipboard winch. The vessel was a crude metal sphere pocked with tiny quartz windows, akin to finger holes in a bowling ball. The plunge was terrifying: leaks could spring, air could dwindle, portholes could collapse. A broken cable would send the bathysphere plummeting into oblivion.

Yet the people inside it—naturalist William Beebe and engineer Otis Barton—were as enchanted as they were frightened. The vividness of the blue light transcended language: "more like an emotion than a color," writes Susan Casey in *The Underworld,* her entertaining account of the technologies and scientists who have shaped deep-sea exploration. The deep was a realm both inhospitable and lively, a place where fear and awe coexisted—"an ungovernable territory," as Casey puts it, "that begins where the sunlight stops."



The Underworld: Journeys to the Depths of the Ocean
by Susan Casey.
Doubleday, 2023 ($32)

Nearly a century after the bathysphere's voyage, it's often said that we know more about deep space than about the depths of our own planet. We've named practically every large moon crater yet thoroughly charted just 25 percent of the seafloor. The ocean isn't less accessible than space; we simply haven't prioritized it. For every dollar the federal government shells out on ocean exploration, it gives hundreds to NASA. The U.S. Navy has 11 aircraft carriers but not one submersible capable of accessing the ocean's deepest spots.

Casey posits that the roots of humanity's aversion run, well, deep. Venturing into space offers "the illusion of expansion" into a limitless cosmos, whereas our ocean sloshes across a planet we feel we've already conquered. It's also just plain creepy. The deep sea is Earth's "haunted basement—sinister, shrouded in blackness, spewing molten rock and poisonous gases, a den of freaky beings and hoary specters."

Happily, not everyone harbors such antibenthic prejudice. This is Casey's fourth marine-themed book. In *The Wave* (2010), she chases gargantuan swells that swallow ships and enrapture surfers; other books sent her in pursuit of dolphins and great white sharks. Those works, however, were set entirely in the ocean's upper strata; meanwhile the deep sea—everything below 650 feet—constitutes 95 percent of Earth's habitable space.

In *The Underworld,* Casey introduces a cast of explorers who have unraveled oceanic mysteries over the past two centuries. First came the dredgers, the scientists who dragged giant shovels behind sailing ships and picked through the biological rubble. Most notable among them was Charles Wyville Thomson, a Scotsman who in the 1860s hauled up glass sponges, sea spiders, and other curiosities—thus debunking a theory that the deep ocean was lifeless. Later came Beebe and other pilots, who took unproven crafts to pressurized depths.

Although none of Casey's *personae dramatis* have Neil Armstrong's name recognition, their journeys have taught us much about how Earth functions. The study of hydrothermal vents has revealed wondrous ecosystems, powered by hydrogen sulfide rather than light, that may hint at life's origins. The investigation of crustal spreading and subduction zones has unveiled the movements of tectonic plates and offered insight into the genesis of dangerous earthquakes. Far from being barren and dull, Casey declares, "the deep is the red-hot center of creation."

Casey isn't the first author to fixate on the deep. In 2021 *Below the Edge of Darkness* and *The Brilliant Abyss,* by biologists Edith Widder and Helen Scales, respectively, covered similar territory. Widder focused largely on bioluminescence, the "living light" that creatures deploy to feed, find mates and deter enemies, whereas Scales concentrated on commercial fishing and other industries that imperil deep-sea ecosystems.

In contrast to those writers, who regard the deep with unadulterated awe, Casey spikes her reverence with levity: one citadel of hydrothermal chimneys reminds her of "Gaudí on an acid trip." Although there is no shortage of biological wonders in *The Underworld,* its author seems most

Illustration by London Ladd

fascinated by how humans have explored a place so hostile to them. This is a book about vampire squid, yes, but also about the technologies that have revealed these creatures, such as sonar platforms and manipulator arms.

And the mechanics of exploration are changing fast. As with space—increasingly a playground for the likes of Bezos, Branson and Musk—the ocean has become the habitat of the ultrawealthy. Casey shadows the Five Deeps expedition, the brainchild of Victor Vescovo, a private equity investor and former navy officer who reminds even his friends of a Bond villain. In 2019 Vescovo became the first person to visit the deepest point in all five ocean basins, a feat he completed in a custom-built submersible—dubbed the *Limiting Factor* in homage to a spaceship in Iain M. Banks's science fiction—that resembles a "padded briefcase" or a "chubby alien's face."

Whether you consider Five Deeps a heroic act of derring-do or a sad testament to how poorly the federal government funds ocean research is perhaps a matter of personal taste. Although the Five Deeps was certainly not without scientific value—Vescovo invited biologists, geologists, and other academics, who documented new species and donated maps to the United Nations—its whiff of machismo and its leader's insistence on doing many dives solo rankled some observers. On Twitter, Julie Huber, an oceanographer at the Woods Hole Oceanographic Institution, lamented Vescovo's "little technical expertise & general disregard for safety."

Vescovo's conversations with Casey won't dispel a reader's suspicion that he's fueled by ego: "I can do whatever I want ... I'm having a blast!" Vescovo tells the writer when they meet aboard his ship en route to the Tonga Trench. Although Casey pays lip service to Vescovo's critics, *The Underworld* would have benefited from a more thorough examination of ocean exploration's politics and power dynamics. In the 21st century, must our most celebrated adventurers remain impossibly rich white guys?

The vainglorious financiers will soon have company—namely, deep-sea mining companies seeking to capitalize on society's surging demand for electric vehicles and other ostensibly "green" technologies. The abyssal plains are strewn with mineral nodules that coalesce around biotic seeds such as sharks' teeth, accumulating cobalt and other metals integral to lithium-ion batteries. Per one mining executive, these troves "literally lie on the ocean floor like golf balls," but acquiring them won't be a benign process. After companies grind up the nodules (and the creatures that adhere to them), Casey explains in one chapter, "the remains will be fire-hosed back into the deep," forming a sediment plume that may smother sensitive life. It's a timely warning: the International Seabed Authority was given until July 2023 to craft the rules that will regulate the nascent industry.

Mining's potential impacts are all the more alarming given how little we know about what we stand to lose. The deep sea's cryptic menagerie features everything from charismatic megafauna such as sixgill sharks to sprawling mats of chemosynthetic bacteria. Casey excels at conjuring the "marvelous weirdos" that glide through submersibles' beams. Dragonfish have "luminous barbels swinging from their chins"; a Pacific sleeper shark possesses "a body as brindled as old granite." The deep sea remains, for now, the planet's grandest wildlife preserve.

At *The Underworld's* climax, Casey finally tours this sanctuary herself when she and Vescovo plummet more than 16,000 feet to the base of a Hawaiian volcano. Like Beebe in his bathysphere, Casey is captivated, and she ably describes the scene for so many of us who will never experience it: "Everything shimmered with a languid beauty, an uncanny gentleness, an amniotic calm."

Although shrimp and jellies abound, Casey is most struck by what she *doesn't* find, chiefly those elements that we feeble surface dwellers consider intrinsic to life. There's no light, no air, no weather, no time. Yet there's a more profound absence, too: an absence of control, of human supremacy, of ego (save, perhaps, for the centimillionaire in the pilot's chair). The deep, Casey writes, is where "you lose your bearings and you find yourself."

Ben Goldfarb is author of *Eager: The Surprising, Secret Life of Beavers and Why They Matter* (Chelsea Green, 2018) and *Crossings: How Road Ecology Is Shaping the Future of Our Planet* (W. W. Norton, forthcoming in September 2023).

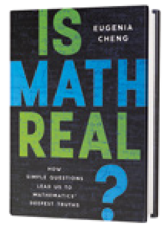
NONFICTION

In Math, No Question Is Dumb

You can find many truths through creative problem-solving

You're likely to identify as either "a math person" or "not a math person," a decisive label you probably received as a child based on your experiences (and grades) in school. Society's persistent assignment of people into—or exclusion of them from—the artificial category of "math person" is the constant worry of mathematician and author Eugenia Cheng, whose latest book attempts to show that math isn't about tedious rigidity that's accessible only to certain people. Rather it's about "increasingly nuanced worlds in which we can explore different things being true."

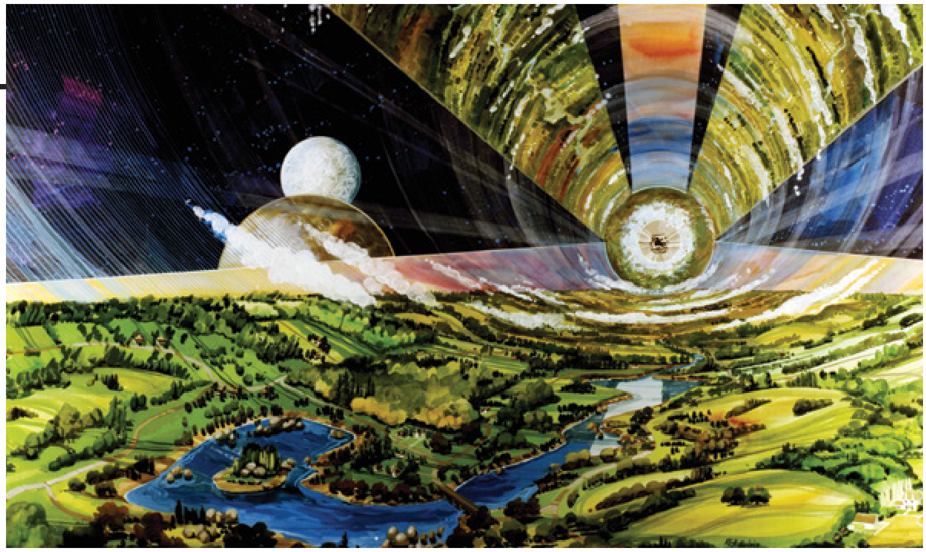
Cheng narrates in a gently instructive first-person voice, inviting readers back into the world of mathematics. In individual chapters, subsections explain the many ways to approach an introductory topic such as multiplication. By walking us through five creative ways to solve 6×8, for example, Cheng successfully demonstrates that "having different ways to think about something constitutes a deeper understanding." Eventually she leads us toward more abstract concepts such as the polar coordinate system, a graphical approach to defining a point using distance and angle, as well as irrational numbers and decimals that repeat infinitely. Despite the complexity of these latter ideas, her use of diagrams and figures helps to reinforce their approachability—although in some cases their incommensurate simplicity feels unsatisfying.



Is Math Real? How Simple Questions Lead Us to Mathematics' Deepest Truths
by Eugenia Cheng. Basic Books, 2023 ($30)

Readers familiar with Cheng's 2020 book *X + Y: A Mathematician's Manifesto for Rethinking Gender* will be accustomed to her tendency to draw parallels between mathematical concepts and social issues. For instance, Cheng describes logarithmic and exponential trends to condemn the denial of COVID-19. She demonstrates how axis manipulation can visually distort infection trends and laments that "far too many people thought [scientists] were fearmongering." This deliberate choice to enter the political fray by injecting her opinions on white privilege, gender roles, "they/them" pronouns and fat shaming invites controversy—and admiration for her conviction.

As the final chapters unfold, Cheng connects her beloved field of category theory—an advanced branch of math that explores relations between objects—with countless personal philosophies, literary references and historic events. Although these ambitious sections would have benefited from more explicit transitions, Cheng's affable style carries her central message through to the end: "You didn't fail math. Math failed you." —*Sam Miller*



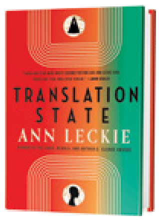
FICTION

Alien Agendas

The interstellar stakes of self-identity

"I had begun to think that maybe it would be nice to have a gender." So declares one of the three protagonists of Ann Leckie's latest brain-bending, genre-crossing space opera. Leckie won nearly all of science fiction's major awards for *Ancillary Justice,* her 2013 novel about an "ancillary," a fragment of a spaceship's artificial consciousness housed in and controlling a human body. It is seeking revenge against the ruler of the Radch Empire, whose own split consciousness is waging explosive war against itself. *Translation State* stands as her richest, most surprising novel since that jewel.

Deeply concerned with what it means to choose one's own identity, from gender to species, Leckie's new book opens with three engaging narrative strands (chapters alternate among the perspectives). Two are relatively conventional in outline but surprising in their particulars: Enae, a shut-in caretaker, is motivated after her grandmother's death to investigate a two-century-old cold case nobody expects her to crack, and space station worker Reet, who dreams occasionally of vivisection, learns of evidence that he might not have been born as human. That revelation, and Reet's insistence that he's certainly human now, sparks a gripping intergalactic legal drama in which all parties, from aliens to AIs, have complex competing agendas. Just as in our world, the identities individuals claim for themselves are perceived by some as threatening to the very foundations of society.



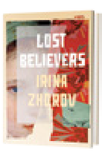
Translation State
by Ann Leckie.
Orbit, 2023 ($29)

More immediately beguiling are the third protagonist's chapters: dispatches from the upbringing of a truly alien mind, bred for mysterious purposes in a fascinating incubator-cum-schoolyard. It's this character, Qven, who after meeting Reet becomes curious about the possibility of gender—and discovers something like love (and the pleasures of binge-watching TV shows). The stakes of Reet's case are both deeply personal and galaxy-shaking, as the outcome could shred the treaty that protects humanity from the mysterious and terrifying Presger, aliens known for "eating" and "copying" the beings unfortunate enough to meet them.

This novel, though a stand-alone story, is the fifth set in the *Ancillary Justice* universe, and readers new to Leckie may find it challenging to keep up with the unfamiliar pronouns, cultures, alien species and politics. Starting with the earlier titles is rewarding but not absolutely necessary because for all her dazzling speculative inventions, Leckie's work is consistently inviting. Her true genre is uplifting, forward-thinking, character-driven science fiction: cozy page-turners attuned to diplomacy, tea drinking, alien minds and the urgent power of self-definition. *—Alan Scherstuhl*

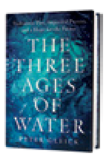
IN BRIEF

Lost Believers
by Irina Zhorov. Scribner, 2023 ($28)



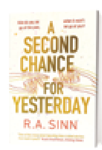
Deep in the Russian taiga, Agafia's days revolve around coaxing survival from the land and practicing her faith free of the religious persecution that her parents fled. Her father's choice to stay in the wilderness protects them from the sinful influences of the outside world—until their lives are upended by an encounter with a geologist named Galina, who is surveying the area for a new mine. Author Irina Zhorov deftly explores the landscape of the two women's lives and the choices they must make as their worlds converge, mapping the forces of faith and fate, progress and preservation onto the backdrop of 1970s Soviet life. *—Dana Dunham*

The Three Ages of Water: Prehistoric Past, Imperiled Present, and a Hope for the Future
by Peter Gleick.PublicAffairs, 2023 ($30)



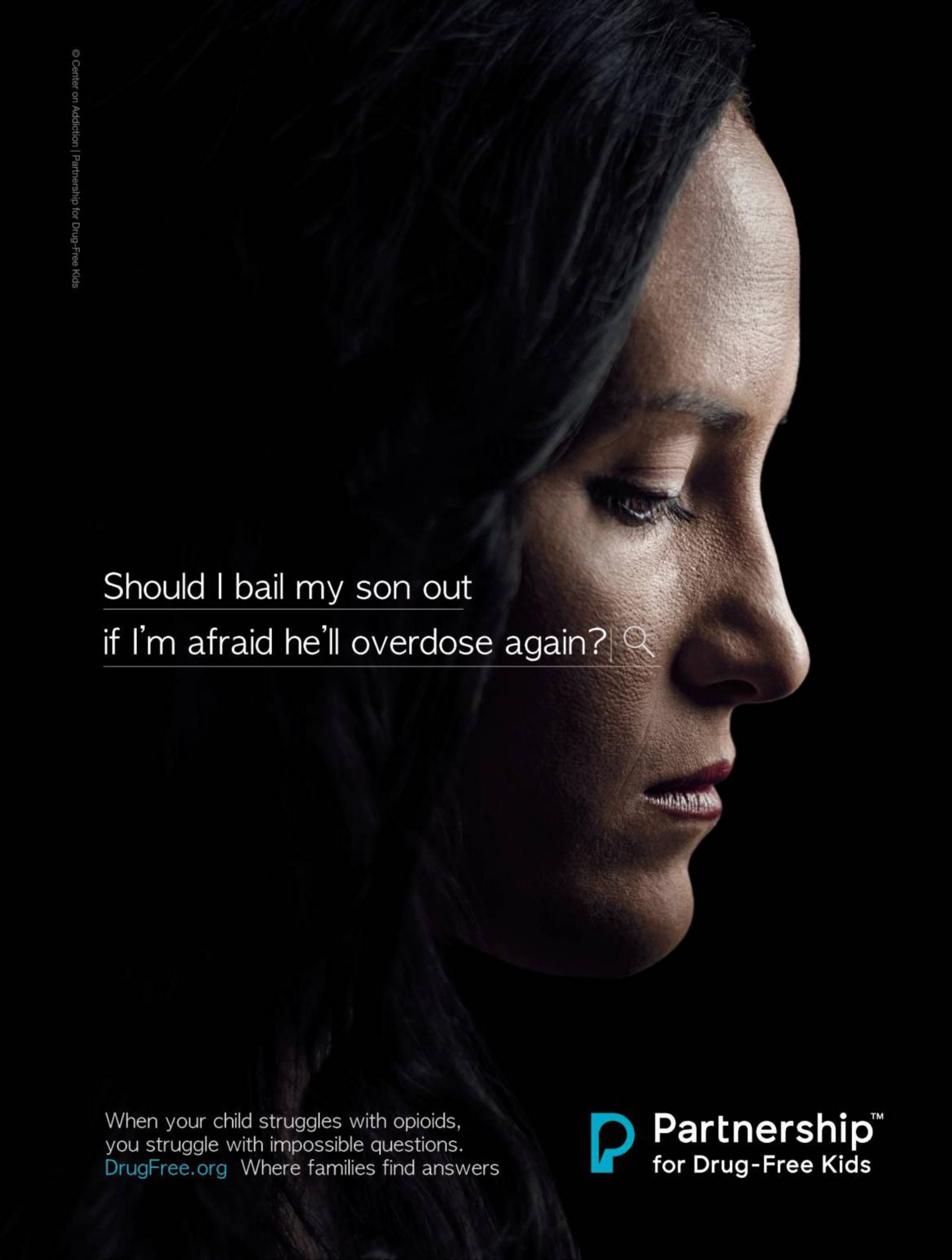
Peter Gleick, author of more than a dozen books on water, orchestrates a voyage through the history of this precious and finite commodity, subdividing a rich timeline into three eras. During the first age, humans innovated to prevail over a seemingly fickle cycle of floods and droughts. The second era, which Gleick says is "our age," brought with it the control of nature in exchange for environmental ransacking, conflict and poverty. He weaves together themes from archaeology, politics and environmental science to show both the need for and the attainable possibility of a sustainable, third age of water in the future. *—Maddie Bender*

A Second Chance for Yesterday
by RA Sinn. Solaris, 2023 ($24.99)



RA Sinn (a pseudonym for siblings Rachel Hope Cleves and Aram Sinnreich) provides a perceptive, mesmerizing time-travel tale of self-revelation and redemption. Programmer Nev Bourne executes the alpha test of Save-Point 2.0, a prefrontal cortex implant that uses loop quantum gravity to let users leap five seconds back in time. But an error in the software propels Bourne back a full day at a time to each preceding yesterday. She exchanges code with a notorious hacker to undo the glitch—and takes time to mend relationships. Sinn's intricately plotted infusion of quantum entanglements and human empathy shows that paying it backward is as valuable as paying it forward. *—Lorraine Savage*

Rick Guidice/NASA Ames Research Center


Should I bail my son out
if I'm afraid he'll overdose again?
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Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *The Big Myth* (Bloomsbury, 2023).

Furious about Firearms

Outrage, not hope, will move us to prevent gun violence

By Naomi Oreskes

At my public speaking events, the most common question I get these days is, "What gives you hope?" In the face of multiple, cascading crises in American life, the pressure is on to be optimistic. To be sure, despair offers little motivation for action. But there can be fine lines between hope, wishful thinking and denial. And sometimes anger and outrage are more appropriate sentiments than optimism and hope.

Consider gun violence, which is now an everyday occurrence in the U.S. In March six people—including three nine-year-old children—were killed in yet another school shooting, this one in Nashville, Tenn. Two weeks later five more were killed in Louisville, Ky. In the aftermath of these tragic events, politicians unwilling to confront the cause of these deaths predictably called for prayers and hope. Tennessee governor Bill Lee spoke of "the desperate need for hope" after the shooting in his state. The problem with hope is that in asking us to imagine a different future, it can distract us from taking meaningful action in the present, such as working to prevent gun violence.

It's no mystery why so many Americans die every year from guns: it's because so many Americans have guns, including extraordinarily powerful, military-style guns that have no justifiable use in civilian life. It's a simple fact that in countries where people have fewer guns, fewer gun deaths occur.

According to the Centers for Disease Control and Prevention, 48,830 Americans died from firearm injuries in 2021—more than died in the entire Korean War. For comparison, the gun death rate across the border in Canada is about 800 a year. Canada has a smaller population, of course, but if it had as many people as the U.S., the equivalent number would be about 7,000.

Canada is no exception: in wealthy countries across the globe, deaths by firearms are far less frequent than in the U.S., and these lower death rates correlate with stricter gun regulation and lower rates of gun ownership. In the U.S., the rate of gun ownership per 100 inhabitants is 120.5; in France, it is 19.6. Switzerland has relatively high gun ownership rates for a European country—one estimate places it as high as 41 per 100—but all guns must be permitted, and no one with a history of mental health problems can get one. The Swiss have not had a mass shooting—defined as one resulting in more than four deaths—since 2001.

Overall, 134 people die from firearms in the U.S. every day. In the European Union, which has more than half again as many people, the number was eight as of 2010.

It wasn't always this way in the U.S. Although guns have long been part of American reality and mythology, the easy availability of assault rifles is a relatively recent phenomenon. According to the Giffords Law Center to Prevent Gun Violence, in the 1980s consumer demand for guns was declining. In response, the gun industry began to make and market military-style weapons. The federal assault weapons ban of 1994 made the transfer and possession of many of these weapons—along with large-capacity magazines—mostly illegal. But the law expired in 2004, and since then there has been no federal regulation of these ultradeadly devices.

They really are ultradeadly. Peer-reviewed studies have shown that mass-shooting-related homicides in the U.S. were substantially reduced between 1994 and 2004, when the federal assault weapons ban was active. One study led by Charles J. DiMaggio, a professor of surgery and an injury epidemiologist at New York University Grossman School of Medicine, found that fatalities from mass shootings were 70 percent less likely to occur during the federal ban. Another study, by the nonprofit Police Executive Research Forum, found that 38 percent of police departments reported a significant increase in criminal use of semiautomatic assault weapons with high-capacity magazines after the ban expired. And that led to increased injury and death because, with rare exceptions, someone with a knife or even a hunting rifle just can't do as much damage as someone using an assault weapon.

Sure, we can hope that something will be done about gun violence. We can remember a time when parents sent their children to school without worrying that they would be shot, and we can imagine a time when that will be true again. Or we can act to change the laws that have created carnage. In the face of this problem with a known solution, the alternative to hope is not despair but rather the galvanizing feeling of factually justified outrage. SA

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Illustration by Izhar Cohen

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

JULY/AUGUST

1973 Crater Mystery Explained

"Why is the earth not covered with meteorite-impact craters as the moon is? Presumably, most of the craters formed in the past have been obliterated by erosion and the dynamic processes of the earth's crust. There are nonetheless at least 14 good-sized craters on the Canadian Shield, some of them dating back nearly 600 million years. According to a hypothesis put forward by Brian Dent of Stanford University, the reason these craters have survived is that they were made in ancient material that was subsequently covered by sediments, which were then planed off by glaciation in comparatively recent times to expose the craters anew."

1923 Mosquito Menace

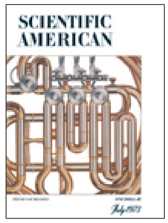
"Using minnows as mosquito policemen, digging huge drainage ditches, fighting the minute parasitic pests with oil and Statewide cleanup activities, mobilizing every agency of modern science to eliminate a menace and peril which jeopardize the rapid settlement of the land of our last frontier—these are the effective measures that the Florida State Board of Health and manifold civic and private concerns are exercising most vigorously in freeing Florida of one of her most unwelcome guests, the objectionable, omnipresent mosquito, the minute musketeer of the insect world who delights in poking its prickly bayonet into human flesh. Floridans [sic] have now arisen and united resources in the most determined campaign against the pestiferous 'bloodsuckers' ever waged in Dixie."

The Accidental Thermos

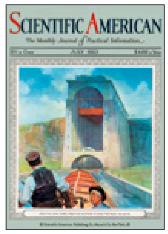
"Sir James Dewar, whose death was recently announced, is popularly known as the inventor of the thermos bottle. However, he was not consciously working for that, but rather for something to preserve liquid gases, with which he was experimenting. The use that his 'Dewar tube' is now mostly put to came as an afterthought. It is true that Dewar used his invention himself for such purposes, but had no intention of commercializing it. He was later able to liquefy hydrogen and he froze it at minus 438 degrees Fahrenheit. He also isolated hydrogen, helium and neon from the air."

Ro: A Universal Language

"Ro is a language, but there is no Land of Ro. It is a tongue made up out of whole cloth. With a knowledge of it, the world would become one nation, for language is a barrier that begets many misunderstandings between peoples. If Ro, or any other of the several machine-made tongues, could be 'put over' in a day—if we could all go to bed saying 'Good Night' and wake up saying 'Good Morning' in Ro—this would soon be a better world to live in. If we could all talk something like this: 'El ye ni cikno uq zad faz ov riceler al kiwap ov temeler ap azod ro,' how much sweeter life would be! But folks won't. The fact is, another 'Ro' is being built now. The world is turning more and more to it as a language of business and commerce: English. There will be a 'universal language,' not so perfect, not so mathematically constructed as Ro. But it will not be Ro."



1973



1923

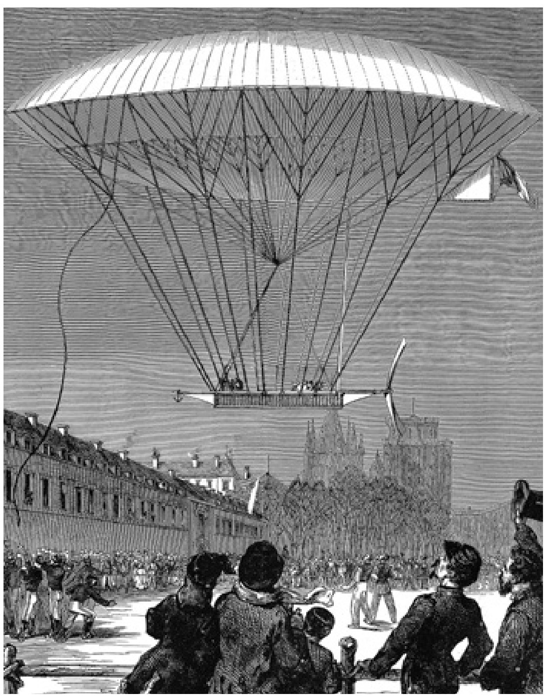

1873

1873 First Underground Railway Is In ...

"The city of Baltimore now boasts a splendid underground railway, the first ever constructed in the U.S. Two distinct lines of tunnels have been made, at an expense of some five million dollars, whereby nearly all of the various railways now entering in the city have their tracks united. The Underground Railway consists of the Baltimore and Potomac tunnel, under some twenty-nine streets and avenues. The Union Tunnel extends under some thirteen streets and avenues."

Bunsen's Burner

"In 1852 Robert Wilhelm Bunsen was nominated professor of chemistry in the University of Heidelberg, which position he still holds. We owe to him important contributions relative to the combustion and diffusion of gases. He is the discoverer of the galvanic battery which bears his name, and which is now most commonly in use. He is also the inventor of that wonderful instrument known as Bunsen's burner. Herr Bunsen, although now in his 62nd year, enjoys excellent health and is still unceasing in the pursuit of his investigations. His style of lecturing is very happy, and has always attracted a large audience."
Bunsen died at the age of 88 in 1899.



1873, Aerial Ship: "We must give attention to the most perfect of aerial machines yet constructed—the aerostat in France. Hydrogen gas is employed. The plane of movement is under control of the aeronaut by rotating a shaft attached to a two-bladed screw. Its recent ascent took place from the Fort Neuf of Vincennes; the descent was commenced at 2 hours 35 minutes, [about 100 kilometers away] at Mondecourt, near Noyon."

Scientific American, Vol. XXIX, No. 4; July 26, 1873

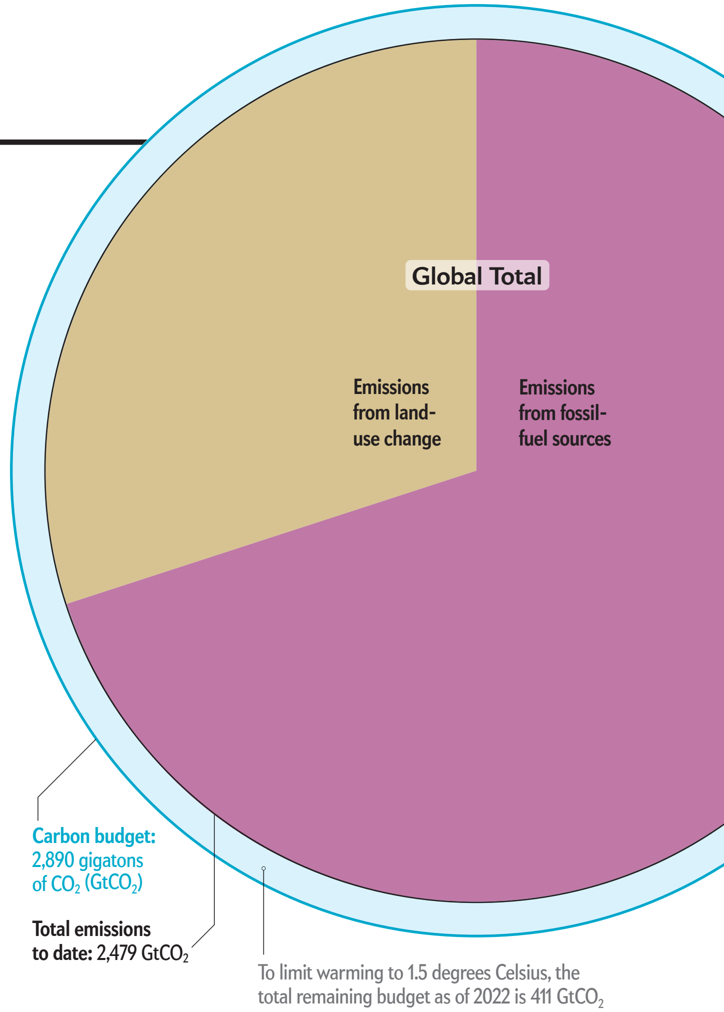
Text by Andrea Thompson | Graphic by Amanda Montañez

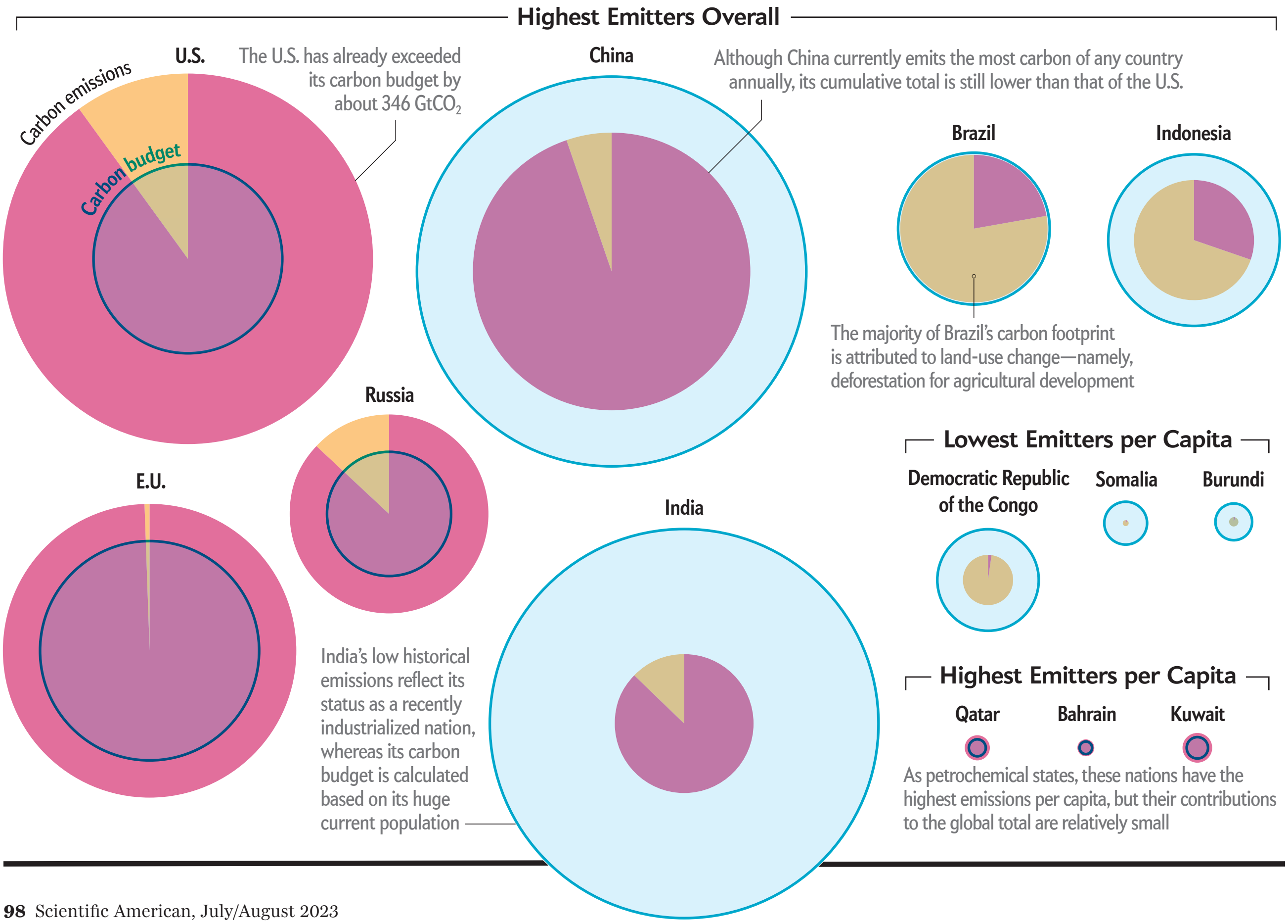
A Fair Share of Carbon

Some countries are using too much of the world's CO_2 budget

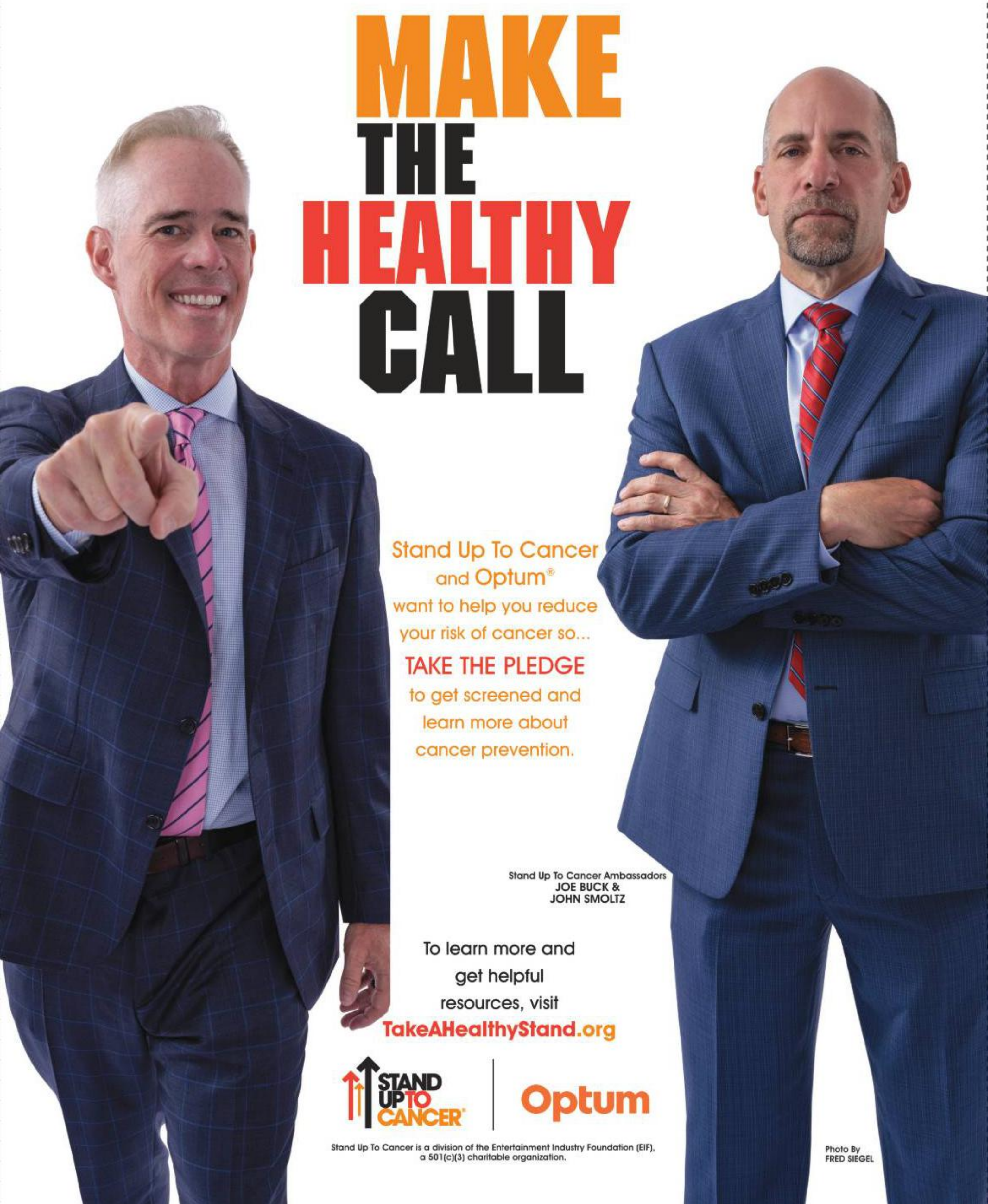
To have a 50–50 chance of keeping global temperatures from rising by more than 1.5 degrees Celsius relative to preindustrial times, Earth's nations need to limit carbon dioxide emissions to about 500 gigatons between 2020 and 2030. With the world currently putting out roughly 40 gigatons of CO_2 per year and emissions continuing to rise, we will easily exceed that budget and keep emitting past 2030.

But countries have not contributed to emissions equitably. A new analysis of the national carbon budgets of a select group of countries shows that the collective European Union and nations such as the U.S. and Russia have produced far more than their fair share, whereas countries that have industrialized more recently, such as India, have not come close to theirs. Developing countries cannot emit their allotment of carbon without worldwide temperature goals being overshot. Therefore, developed nations need to cut their emissions much more aggressively and provide financial and technological support for renewable energy in the developing world, experts say.





Sources: *Climate Change 2021: The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC, 2021 (carbon budget); *Supplemental Data of the Global Carbon Budget 2022.* Global Carbon Project, 2022 (emissions data); World Bank (country populations and per capita emissions data); Data analysis by Amanda Montañez and Piers Forster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Enhancing
Human Touch