SCIENTIFIC AMERICAN

Refreezing the Arctic

Your Mitochondria, Your Health

The Quantum Bubble That Could Destroy the Universe

The Sunshine Cure

The discovery that sunlight boosts your immune system is leading to new disease-fighting therapies

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FEATURES

Photograph by Taylor Roades

SCIENTIFIC AMERICAN

ON THE COVER
Sunlight can boost your immune system and reduce certain diseases. The discoveries began as researchers found that illnesses such as multiple sclerosis are less common at tropical latitudes, where there is more sunlight. Experiments showed that wavelengths of ultraviolet light that don't cause skin cancer can help disorders that involve a hyperactive immune system. Small boxes that emit UV light are already showing promise in therapy.

Illustration by Taylor Callery

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Hopeful Sunshine and Quantum Bubbles

WE FLOCK TO BEACHES FOR IT, cats and other animals bask in it, the quality of photographs lives and dies by it, and a person's mood (and vitamin D level) gets a boost from it. Although it has known risks, sunlight also seems to hold immense restorative value. Now scientists are finding the sun's rays could truly help to quash some autoimmune diseases. In our cover story on page 22, journalist Rowan Jacobsen introduces us to Kathy Reagan Young, who was diagnosed with multiple sclerosis (MS) in 2008 and took up phototherapy relatively recently. She stands in front of a light box every morning, her torso engulfed in ultraviolet rays for just minutes at a time. Since starting the therapy, her brain fog and fatigue have nearly vanished in what Young calls a "UV-fueled rebirth." In this hopeful feature, Jacobsen also meets with scientists who are trying to figure out how UV light calms a person's immune system. Advocates say a better understanding of this process could lead to "an Ozempic for autoimmunity," he writes, referring to the blockbuster weight-loss drug.

Rather than taking in warming sunbeams, some researchers want to repel them and turn down global temperatures by refreezing a swath of Arctic ice as big as the combined area of Texas and New Mexico. The gargantuan geoengineering project would require half a million underwater drones to pull water from below the melting ice cap and spray it onto the surface to freeze. On page 40, climate journalist Alec Luhn recounts his visit to an Inuit village in northern Canada where scientists are testing out the ice-thickening technique. As with all geoengineering ideas, he finds, there's no guarantee this scheme will work or way to know for certain whether there will be negative consequences. But polar scientists who spoke to Luhn say humanity needs a stopgap until the world can wean itself off greenhouse-gas-emitting coal, oil and natural gas.

The drive to find answers is what propels many scientists. One nagging question remains: Where did we come from? Now cutting-edge radio astronomy is helping cosmologists peer back in time to the very start of the universe, when only Hula-Hooping particles existed. No moon. No Earth. No Milky Way. No light. *Scientific American* contributor Rebecca Boyle eloquently describes exciting new telescopes and experiments aimed at detecting signals from the wriggling atoms spilling out of these so-called cosmic dark ages (*page 32*). In addition to learning how the universe took shape, scientists hope to get intel on how the first light was released and the first galaxies formed.

Physicist Matthew von Hippel (*page 58*) looks not at the birth of the universe but at its destruction, outlining a disastrous world-ending scenario that makes asteroid strikes and Earth-colliding black holes look like kid stuff. Called vacuum decay, this apocalyptic event would result from the emergence of a new quantum state. Here's how: The value of the Higgs field that pervades all of space would have to increase—something physicists liken to rolling a boulder up a hill. The field change would manifest in a quantum bubble, which, if big enough, could expand at the speed of light, ultimately making matter—and therefore life—impossible.

Scientists had assumed that all major renovations to our genomes had happened long ago and that any recent evolutionary changes were few and far between. But advances in DNA-sequencing technology have revealed that even in recent millennia, humans have continued to evolve in substantive ways. These changes helped us to conquer every corner of Earth, writes journalist Kermit Pattison (*page 64*). "We are like rats or cockroaches—extremely adaptable," says one scientist who spoke with Pattison.

If you look up "mitochondria" in a biology textbook, you'll find a definition that is some variation of "powerhouses of the cell." But accumulating research shows these organelles are also social beings that orchestrate the inner workings of the cell; they even communicate with and help one another. Of course, when mitochondria malfunction, diseases can ensue. Behavioral neuroscientist Martin Picard's passionate profile of mitochondria in this issue (*page 50*) gave me a lesson in not only the value of basic science but also the wonders of life.

Jeanna Bryner
is interim editor in chief
of *Scientific American.*


Hey. Why don't you see my value?
—Earth
Our planet is talking to us.
The Global Futures Laboratory is listening and working to build a healthier relationship with it. With a holistic, life-systems approach to solving critical resource challenges, we're driving toward a future in which all living things thrive. Join us.
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ASU
Julie Ann Wrigley Global Futures Laboratory
Arizona State University
Reshaping our relationship with our world

JENNIFER N. R. SMITH
THE SOCIAL LIVES OF MITOCHONDRIA

PAGE 50 In 2020, on a trip to Devon, England, Jennifer N. R. Smith (*above*) went swimming in the sea. Just as night fell, the water began to glow with light from bioluminescent algae. "It's electric blue," she recalls. "If you lift your arm up out of the water, it kind of sparkles all over your skin. It was the most magical experience I've ever had." Smith, who had just finished a program in medical illustration, felt she had to draw this phenomenon immediately.

Smith took inspiration from that experience to create her own style of illustration, which combines the traditional textures of collage and paper marbling with a technique called reverse stippling—pinpricks of light over a dark background. The technique evokes wonder in her for the natural world, with the dots representing more than just flecks of algae on her skin. "They could be the night sky or atoms, either the macro or the micro."

For this issue's feature story on the mysteries of mitochondria, by behavioral neuroscientist Martin Picard, Smith visualized the organelles' zigzagging inner walls by using this illustration method to "turn the mitochondrion into a labyrinth." Rather than explaining concepts to readers with her drawings, she tries to invite them in by inspiring a sense of awe. "If you can spark wonder within someone about a certain topic," she says, "they will interact with it in a way that's much more deep and authentic."

ALEC LUHN
REFREEZING THE ARCTIC

PAGE 40 In February climate journalist Alec Luhn took four days and four planes to travel to Cambridge Bay in Canada's Nunavut territory. It was his second trip to the Arctic Circle for *Scientific American*—in 2023 he went to Alaska to investigate why rivers in Kobuk Valley National Park were turning orange. This time, while reporting on efforts to refreeze parts of the melting Arctic to stall the worst effects of climate change, he was struck by just how fast the environment was changing.

"This is the Northwest Passage—the holy grail of ocean exploration for 400 years," Luhn says, referring to the famed sea route connecting the Atlantic and Pacific Oceans. Many colonial explorers died trying to navigate the ice-clogged sea lane, "but now that ice is melting to the degree that cruise ships go through the Northwest Passage every single summer," and local Indigenous communities, he says, are struggling to maintain a way of life that depends heavily on sea ice for hunting, transportation, and more.

As Luhn observed the efforts to refreeze the melting cap, he often thought about how this harsh environment has made a mockery of colonial expeditions' efforts to bend it to their will. "And here we are now again, trying to bring our technology to bear on the forces of nature" to counteract the melting we continue to cause, he says. "Will we succeed this time?"

ROWAN JACOBSEN
CAN SUNLIGHT CURE DISEASE?

PAGE 22 For the past few years science journalist Rowan Jacobsen has been fascinated by the effect of light on our bodies. "We tend to think of light as ephemeral," he says, yet it is physical—we're constantly bombarded by photons, little packets of energy. "There's no way it couldn't have a health impact, in a way," he says. Indeed, research across fields of medicine has shown that people exposed to more light tend to have better health outcomes. In our cover story for this issue, Jacobsen explores new phototherapies for autoimmune conditions such as multiple sclerosis.

Jacobsen has written several books, on topics including oysters, truffles and chocolate. Food, he says, is a "clandestine" way to get people interested in the natural world. For his next book, about how light affects health, he recently embarked on a "self-experiment." Jacobsen rented a 1962 Airstream in southwestern Arizona and spent a month without artificial light at night. After sunset "there's nothing to do [except] lie out and look at the stars," he says.

Jacobsen had returned to his home in Vermont just before we spoke for this interview, and he reported feeling refreshed. "My energy and my focus were awesome," he says, attributing the improvement mainly to the early mornings. "Less [artificial] light at night was good, but I think the bright sunlight in the morning was equally important."

JAY BENDT SCIENCE OF HEALTH

PAGE 84 Jay Bendt fell into her illustration career "sort of backward," she says. She had planned to take the path of many members of her family and become a doctor. But during her first year of college, she expressed interest in drawing on an administrative form and was unwittingly sorted into an art-focused track. "Being very young, I was like, 'You know what, that actually doesn't sound like a bad idea,'" she recalls. Bendt had grown up drawing in the age of DeviantArt, an online art platform popular in the 2000s, and had been inspired by the "magical girl" aesthetic of *Sailor Moon* and other anime. After graduating with a painting degree, she learned to integrate these interests with formal, conceptual skills to become a freelance illustrator.

Bendt illustrates *Scientific American*'s Science of Health column, written by Lydia Denworth. This issue's column about the impact of exercise on gut bacteria was a particular challenge. "Anything that has bacteria in it is one I need to think on more" to make it original, she says; it's too easy to fall back on drawing little anthropomorphic cells. For editorial illustrations, Bendt picks a style that matches the story, but her personal work is unfailingly whimsical. "I try to make work that, once you've caught a glimpse, you have to look at it."

Charles Smith

ORBITAL DEBRIS

The article "How to Recycle Space Junk," by Moriba Jah, addresses how cluttering space with detritus will have, and is having, a deleterious effect on various activities, particularly in low Earth orbit. Why not design major satellites with a small thruster that, when a satellite nears the end of its life, will push it into a trajectory that will take it into the sun? Oh, pollution of the sun, you say? Can that occur from sending a chunk of metal and silicon—even one that is boxcar-size or bigger—into a fusion furnace?
HAROLD SHAW *PENOBSCOT, ME.*

Jah rightly focuses on junk in Earth orbit. Attention should also be given to junk in orbit about or on the surfaces of other bodies in the solar system, however. This is especially true of bodies that may have human-occupied facilities on their surface or in orbit about them in the future.
JAMES W. SCOTT *VERNON, N.J.*

JAH REPLIES: *Shaw's idea is intriguing. There are a few significant challenges to consider, however. The approach would require a considerable amount of energy because Earth's orbital velocity around the sun is extremely high, and a satellite would need to be deorbited to head into our star. That is far more energy-intensive than just pushing it slightly into a lower orbit. And the trajectory would require a very precise launch window. Otherwise the satellite could just end up in a different orbit around Earth and, worse, could collide with other satellites. Moreover, although this plan could indeed have a very minimal effect on the sun's fusion process, the risks of creating a concentrated debris field in certain regions of space or inadvertently triggering an unwanted chain reaction would remain. And the environmental cost of the needed fuel could be significant. An alternative, which is currently being researched, involves using robotic "tugboats" that would rendezvous with defunct satellites to push them into a safer orbit or to reenter Earth's atmosphere, where they would burn up. Another idea is to capture space debris with specialized nets or harpoons.*

Scott is absolutely right that as human exploration and activity expand to bodies such as our moon and Mars, we must consider the potential for space debris to accumulate there as well. Such objects not only would pose a collision risk to future spacecraft but also could complicate the long-term sustainability of lunar and Martian settlements. Methods for mitigating space junk around the moon or Mars could include "cleanup" missions using robotic systems to collect and deorbit it or even the development of infrastructure to prevent it from accumulating in the first place. New international frameworks will need to be developed to address these challenges.

February 2025

REPRESENTATION IN SCIENCE

In "Marie Curie's Hidden Network" [Q&A], Clara Moskowitz talks to author Dava Sobel about her book regarding Curie and the women who worked in the famous scientist's laboratory. In the discussion, Sobel emphasizes that Curie's approach to recruiting female scientists was characterized by a neutral stance—that "she had nothing *against* hiring [women]."

When observing videos of enthusiastic groups in technical roles, I often find myself morbidly counting the people of color. Women have become relatively better represented in science, but people of color remain glaringly less so. Ideally, candidates are chosen based on résumés and credentials. But studies consistently show that résumés with names suggesting people of color receive significantly less interest than otherwise identical ones. This effect is often demonstrably subconscious, suggesting that to be selected, such individuals need to stand out—echoing Curie, who went on to win two Nobel Prizes, defying stereotypes.

As we navigate into an uncertain future, let us take a moment to recognize that it required a scientist of Madame Curie's extraordinary caliber to remind us of the essential work that is still needed to harness the full potential of all available human capital.
K. CYRUS ROBINSON *TAMPA, FLA.*

TEEN BRAIN DEVELOPMENT

"Growing the Adolescent Mind," by Mary Helen Immordino-Yang, identifies adolescence as a time of opportunity for growth. "Transcendent thinking" is used throughout the article to describe the ability to "muse in an abstract way" about a given situation, including by considering different cognitive perspectives. This phrasing is misleading. "Transcendent thinking" usually refers to mystical or "peak" experiences, which are ineffable, holistic, and outside of time and space.

Immordino-Yang also claims a cause-and-effect process in which reflective, emotional thinking makes brain networks communicate more effectively. It could instead be that changing brain connections allow for the expansion of reflective and emotional thinking. The author notes neuroscientist Antonio Damasio's work with a patient known as EVR, whose case involved the latter causation: as described

"It required a scientist of Madame Curie's extraordinary caliber to remind us of the essential work that is still needed to harness the full potential of all available human capital."
—K. CYRUS ROBINSON *TAMPA, FLA.*

in the article, brain surgery changed EVR's social and emotional intelligence.

Encouraging adolescents to see the bigger picture is important, but we must work with their current brain capacity.
FREDERICK TRAVIS *FAIRFIELD, IOWA*

IMMORDINO-YANG REPLIES: *Travis points out a common misunderstanding. My colleagues and I coined "transcendent thinking" to describe thinking that is abstract and "transcends," or "moves beyond," the concrete here and now. "Transcendental" refers to mystical or out-of-this-world experiences (although some have used "transcendent" this way).*

It is also a good point that we cannot prove that teens' transcendent thinking causes brain development. It cannot be only that changing brain connections allows this thinking to occur, however. In my team's study of teenagers in Los Angeles, the level of transcendent thinking at the beginning of the study predicts future brain development, irrespective of the teens' brain development at the start. The level of transcendent thinking also does not correlate with brain maturation at the study's start. Our data are consistent with an at least partly causal explanation, and we are now working to demonstrate this conclusively at the University of Southern California's Center for Affective Neuroscience, Development, Learning and Education (https://candle.usc.edu).

A SPLOTCH, A BLOTCH

It's interesting that the February issue has two feature articles about "blobs": "Anatomy of a Supernova," by Clara Moskowitz, and "A New Understanding of the Cell," by Philip Ball. But the two types of blobs couldn't be more different and are many orders of magnitude different in size.
CHRIS LANDRY *HUDSON, N.H.*

ERRATA

"Redefining Time," by Jay Bennett [March], should have given the full English name of BIPM as the International Bureau of Weights and Measures.

In "The Missing Planets," by Dakotah Tyler [March], the deck summarizing the article should have said that exoplanet demographics reveal a puzzling lack of worlds in a certain size range.

ADVANCES

ANIMAL BEHAVIOR

Mother-Daughter Signal

A chimpanzee's gesture reveals secrets of ape communication

AN HOUR'S DRIVE down a ragged dirt road, deep in the heart of Uganda's Kibale National Park, a small research camp sits in the middle of chimpanzee territory. Tangled vines drape ancient trees in the forest, and equatorial sunsets ignite the sky, savannas, lakes and misty mountain peaks in molten gold and ember red. For the primatologists stationed here, mornings begin with a map of yesterday's chimp movements, a tally of fruiting trees and an ear tuned to the forest. The apes' calls start early with low, rolling "pant-hoots" that ripple through the canopy. On some days the chimps are close by. On others the scientists search for them for hours, winding through the Ngogo chimpanzee community's home range of 35 square kilometers (an area more than half the size of Manhattan) along a grid of well-worn trails.

On one such morning in 2019 a few researchers spotted something curious: Lindsay, a chimpanzee around two years old, reached forward from her mother Beryl's back to cover the older chimp's only functioning eye. At first it seemed like a fleeting moment of play. But the scientists later learned that Beryl, who moved attentively through the undergrowth with occasional pauses, responded to her daughter the same way every time: by stepping forward. Within a few years the gesture seemed to become an intentional "let's get moving!" signal between the two.

What might have started as Lindsay's simple, spontaneous attempt to get her mother's attention—by blocking Beryl's already limited vision—over time took on a shared meaning akin to a secret handshake or inside joke. Among the Ngogo chimpanzees, researchers are coming to realize that such behaviors are not random quirks but part of a growing picture of how apes develop and transmit culture.

"This is fascinating from a [scientific] literature perspective because there had been no prior record of this gesture," says primatologist Bas van Boekholt, now at the University of Zurich, who led a study published recently in *Animal Cognition* to decipher the gesture's meaning. In 2022, during his second field season at Ngogo, van Boekholt was reviewing video footage from his field assistant when he first noticed Lindsay's hand-on-eye behavior. Among nonhuman primates, previous examples of gestures that were unique to particular individuals had been documented only in captive environments, he says. "We haven't had convincing evidence that they occur in the wild," van Boekholt adds.

Curious about whether others had observed Lindsay making the same gesture, van Boekholt reached out to fellow researchers and field assistants. Isabelle Clark, a biological anthropologist at the University of Texas at Austin, recalled being among those who had spotted the behavior as early as 2019. "This is a big deal because this gesture isn't part of the common chimp repertoire. It's not in our chimp-gesture dictionary, so to speak," she explains.

To investigate further, researchers from various field seasons conducted a collaborative quantitative analysis of 179 videos of Lindsay and Beryl that included 21 instances in which Lindsay used the gesture. Young chimps are known to be playful while riding on their mother's back, and the scientists scrutinized Lindsay's behavior: Was she simply brushing her mother's eye coincidentally? The data suggested otherwise.

Van Boekholt's team also reviewed more than 1,020 video clips of 12 other mother-child pairs within the Ngogo chimpanzee community and found only three isolated

instances in which other chimps performed the gesture. In each of those cases, the movement was made just once, without the same intentionality markers present in Lindsay and Beryl's interactions. "At this point," van

Kevin C. Lee

Chimpanzee Lindsay and her mother, Beryl, created a special signal that has scientists intrigued.

Boekholt says, "we feel confident in saying this is an idiosyncratic gesture."

Clark, who specializes in social behavior development in juvenile and adolescent chimpanzees, says that chimps exhibit foundational elements of symbolic communication—the ability that lets humans create limitless symbols for different meanings—and that gestures similar to Lindsay's could be the building blocks of eventual humanlike communication.

"There are multiple theories on how gestures develop in primates, particularly great apes," van Boekholt says. "Tracking their development over a lifetime offers clues about the evolution of language and communication."

The researchers note that if the hand-on-eye gesture exists in other chimpanzee communities, it probably carries a different meaning there. Cat Hobaiter, a primatologist and field scientist at the University of St. Andrews in Scotland, who was not involved in the study, cautions against drawing broad conclusions from a single chimpanzee group. "It's like trying to describe human civilization after only visiting Paris, Shanghai and Auckland," she says. Just as customs and traditions differ across human cultures, gestures among chimpanzees can vary widely; a signal of reassurance in one group might mean something entirely different, or nothing at all, in another.

The development of Lindsay's gesture, Hobaiter says, suggests that apes—like humans—have the capacity to form particular shared uses of a signal, regardless of whether they're created from scratch. She cautions against overemphasizing uniqueness at the expense of a broader insight: the more we observe ape cultures, the more depth we see in them. Chimpanzees and bonobos share nearly 99 percent of their DNA with humans. And their traditions, social learning and communication reveal a continuum rather than a sharp divide between us and other great apes.

Van Boekholt has returned to Uganda, where he is once again studying the mother-daughter duo. Lindsay, who is old enough to walk independently, still clings to her mother—and continues to use the gesture. Van Boekholt suspects Beryl may be pregnant, and he is eager to see whether Lindsay's potential future sibling will adopt the gesture and thus turn it into a family tradition. If social learning plays a role, he notes, the gesture is likely to persist.

"Any parent of a newborn understands the private language they share with their child—meanings that others would never recognize. Now we're seeing a similar phenomenon unfold in the wild," he explains. For Lindsay, "logically, blocking her mother's vision seems counterintuitive, the last thing she'd want to do. Yet, for some reason, [Lindsay and Beryl have] created this shared meaning between them, and I think that's just really wonderful."

—Avery Schuyler Nunn

PSYCHOLOGY

Romantic Hopes

Men actually crave romantic relationships more than women do

DO YOU THINK WOMEN are more invested in romance than men are? Rom-coms, TV commericals and women's magazines may reinforce this stereotype, but psychological research is increasingly telling a different story: multiple studies have suggested that men may actually place greater importance on romantic relationships. Now researchers have identified a key behavioral factor that could explain this surprising difference.

Drawing on more than 50 studies of mixed-gender relationships, researchers at Humboldt University of Berlin, the University of Minnesota and Vrije University Amsterdam proposed that men, compared with women, expect to gain more from being in a romantic relationship and are thus more motivated to find a partner. According to multiple anonymous surveys, men also tend to experience greater mental and physical health benefits from being in a relationship, are less likely to initiate breakups, and struggle more with the emotional toll of a breakup, the researchers wrote in *Behavioral and Brain Sciences*.

Elaine Hoan, who studies social psychology at the University of Toronto, says these observations align with a trend she has seen in her own research: "single men are typically less happy with their singlehood than single women, even across different Western and Eastern cultural contexts."

The authors of the new paper suggest that men's greater reliance on romantic relationships stems from differences in emotional expression, which can often be traced back to childhood. One study in the analysis found that U.S. adults view three-year-old boys who are described as sensitive and emotional as less likable than boys with stereotypically masculine traits. Other studies showed that parents use more language related to emotions with daughters and reward them for expressing sadness and fear while punishing sons for the same behavior.

"From an early age, boys are discouraged from expressing vulnerability," says Humboldt University social and developmental psychologist Iris Wahring, co-lead author of the new paper. And the social norm "continues into adulthood," she explains. This cultural standard makes men less likely to seek emotional support from friends and family compared with women. As a result, men rely more heavily on their romantic partners to fulfill these needs. Women, in contrast, seek emotional support from a wider social network and thus tend to be less dependent on romantic partners.

Mariko Visserman, a psychologist at the University of Sussex in England, says the review "does a wonderful job in explaining how gendered norms and experiences early in life can set the stage for the differences between men and women's relationship benefits and vulnerabilities later on."

The key takeaway is "that we all need to feel embedded in a supportive network of relationships," Visserman says. She adds that it's wise to invest in relationships beyond romantic partnerships—both to have a support system when a romantic relationship goes through a rough patch or ends and to meet various emotional needs.

An important implication of these findings is the need to foster a culture in which men feel encouraged to build strong, emotionally supportive friendships outside of romance, Hoan says. She notes that "this means challenging traditional gender norms that stigmatize male vulnerability and promoting the value of more meaningful friendships for men."

—Clarissa Brincat

Thomas Barwick/Getty Images

Shaky Strategy Territorial caterpillars vibrate ferociously, then swing away like Spider-Man

ANIMAL BEHAVIOR When facing an intruder, animals generally tend to fight, flee or simply freeze. But certain baby caterpillars do something else entirely: they vibrate.

Newly hatched warty birch caterpillars, each smaller than a single sesame seed, live and feed alone on the very tips of leaves. In a recent study in the *Journal of Experimental Biology*, scientists found that the caterpillars are fiercely protective of their little abode. If another caterpillar wanders into their territory, these tiny critters start furiously drumming their heads, shaking their bodies and scraping their butts against the leaf—a series of complex vibratory behaviors to signal that their leaf tip is off-limits.

This research "takes me into how complex the sensory world of even a tiny, tiny organism is that humans are just not aware of," says Jayne E. Yack, a neuroethologist at Carleton University and senior author of the new study.

> The tiny caterpillars' vibrations "are like lion roars." —Jayne E. Yack *Carleton University*

The scientists used close-up videos and a laser-doppler vibrometer—an instrument that can pick up a leaf's vibrations without touching it—to tap into the caterpillars' shaky world. "For such small caterpillars, [their vibrations] are like lion roars," Yack says. "You have to turn down the volume and take the headphones off your ears because they're so loud." The bouncy leaf tip may also boost the sound, she adds.

The caterpillars most likely guard their leaf tip because it offers a good escape route. If an undeterred intruder continues to approach, the caterpillar drops a silk thread and flees like Spider-Man. But its warning wiggle often does the trick.

These vehement vibrations could also be a bluff; some spiders make similar moves. "It's a distinct possibility that they're mimicking a spider to deter somebody else from taking over their precious leaf tip," Yack says.

Like singing birds, "these caterpillars are also declaring ownership of their territories and competing with rivals—in this case by sending vibrations through the leaf surface rather than the air," says Andrew Mason, who studies animal communication at the University of Toronto Scarborough and was not involved in the study. "This paper gives us a window onto this otherwise undetectable world." —*Rohini Subrahmanyam*

Illustrations by Thomas Fuchs

ENVIRONMENT

Duty to Warn

Labeling dangerous chemicals shifts cleaning-product formulas

REQUIRING WARNING LABELS on products with potentially toxic ingredients can obviously help keep them out of a careful consumer's shopping cart. But a recent study shows that these "right-to-know" laws may also halt such formulations long before they hit the shelves or are released into the air—and can even protect people outside a law's geographic range.

One of the most significant such laws ever passed in the U.S., California's Proposition 65, requires businesses to post a warning when chemical exposures, whether through product ingredients or air emissions, exceed a safe standard. For the recent study, published in *Environmental Science & Technology*, researchers interviewed business leaders and found that California's rule has caused many companies to reformulate their products by reducing amounts of flagged ingredients to safer levels—or by dropping them entirely.

The interviews covered dozens of industries such as cleaning products, electronics and home improvement. They included top-earning brands across all sectors as well as leading green cleaning brands—although the companies remain anonymous in the study, says lead author Jennifer Ohayon, a scientist at the nonprofit research organization Silent Spring Institute.

Ohayon and her colleagues found that companies commonly replaced the warning-requiring ingredients altogether, in part to avoid possible litigation. Michael Freund is a lawyer who spent decades representing groups aiming to stop toxic chemical emissions; he says the California proposition's incentives can help fill a key gap. In the cases he worked on, "every one of those companies had permits that allowed them to do what they were doing," he says. "And that's where Prop 65 comes into play."

Although the 1986 law is specific to California, the study results suggest its effects cross state borders as manufacturers reformulate their products nationally. A parallel study published last year by the Silent Spring Institute backs this idea up with data. That study looked at levels of 37 chemicals in blood and urine samples among both Californians and non-Californians. Of the chemicals, 26 were listed in Prop 65, and samples from before and after listing were available for 11 of those, which allowed for a comparison. For most of the chemicals, levels in people's bodies decreased after listing—both in California residents and across the nation.

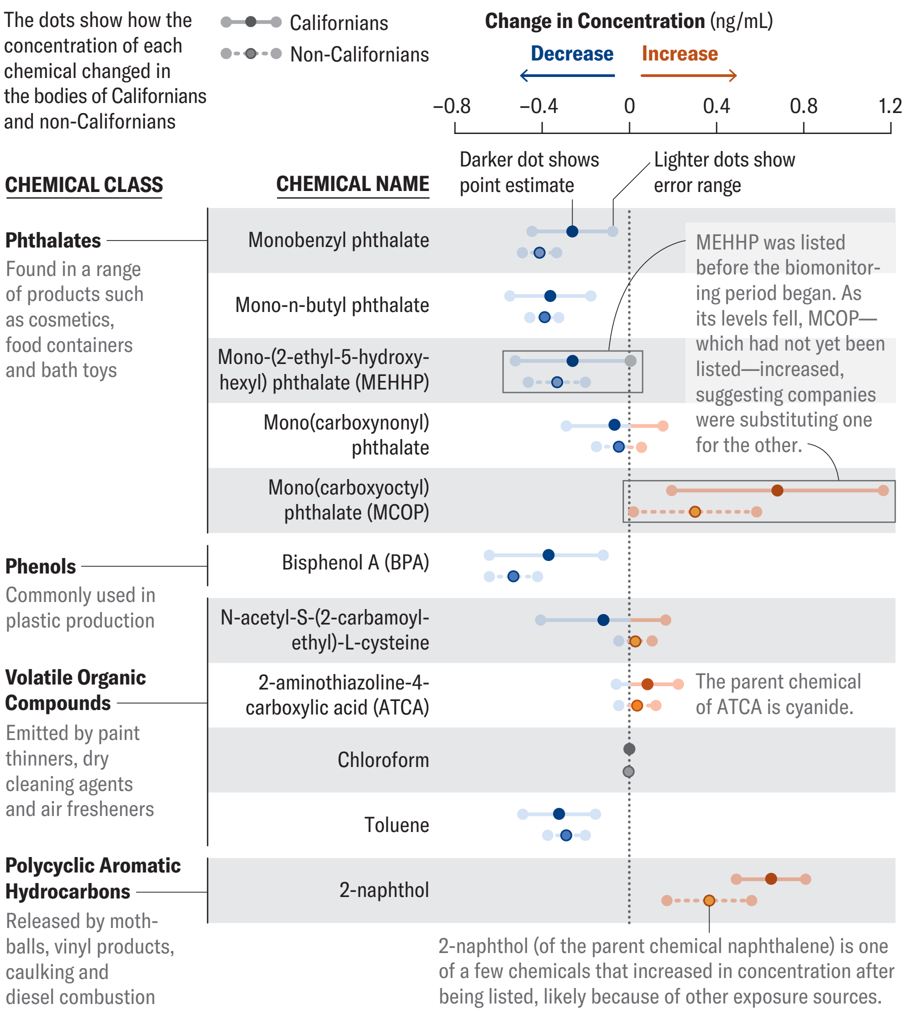
Megan Schwarzman, a researcher involved in both studies, says sample data exist for only a tiny fraction of the 900 Prop 65 chemicals. In a metaphorical game of Twister, the researchers had to figure out what publicly available data could be matched to Prop 65 chemicals because "the data weren't collected for that purpose," Schwarzman says. Monitoring all listed chemicals over time in future work would show any patterns much more clearly.

The new study notes that Prop 65 is sometimes criticized for leaving Californians "over-warned" and "under-informed." But the research so far suggests that regardless of consumer effects, the policy has guided at least some businesses' choices—raising the bar for everyone.

—Ripley Cleghorn

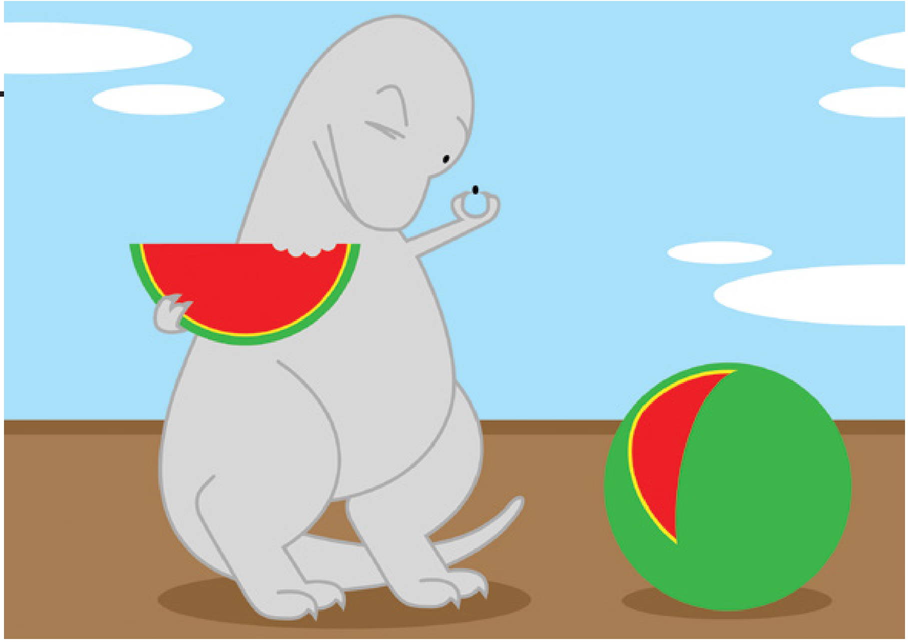
Tracking Chemical Exposure through Biomonitoring

Researchers used data from the U.S. National Health and Nutrition Examination Survey (NHANES), which measures chemical concentrations in blood and urine samples, to evaluate the effect of California's Proposition 65 on companies' use of toxic chemicals found in common household products. The chart shows changes measured in people at the higher end of the exposure distribution (75th percentile).



Source: "Trends in NHANES Biomonitored Exposures in California and the United States following Enactment of California's Proposition 65," by Kristin E. Knox et al., in *Environmental Health Perspectives*, Vol. 132, No. 10; October 2024 (*data*)

Graphic by Ripley Cleghorn



Mesozoic Logging Dinosaurs curbed fruit seed sizes—and humans may, too

PALEONTOLOGY What do humans have in common with the dinosaurs that trampled through ancient forests? It turns out that both may have a surprising impact on the size of seeds in the fruits growing around them. When researchers mapped the evolution of seed sizes onto that of land animals, they observed that when land animals got bigger, so did fruit seeds—with a few outsize exceptions. A recent study in *Palaeontology* illustrates how, over the course of natural history, gigantic megafauna such as dinosaurs curbed the growth of seed sizes by physically altering the ecosystem, influencing forest light levels. Today that role may be filled by a much tinier species: humans.

The idea that land animals can alter their environments is "fairly straightforward and well substantiated in a variety of scales," explains Clive G. Jones, an ecologist at the Cary Institute of Ecosystem Studies in Millbrook, N.Y., who was not involved in the new study. For instance, savanna elephants push down trees and tear at shrubs, transforming the plant landscape. But even this elephantine influence is minor in comparison to that of prehistoric creatures.

The researchers' new model suggests dinosaurs caused a level of destruction that suppressed an evolutionary tendency for seeds to grow bigger, says study lead author Christopher E. Doughty, an earth system scientist at Northern Arizona University. Bigger seeds tend to attract bigger animals for dispersal and to sprout taller plants, Doughty explains; both factors can give plants better access to sunlight in crowded conditions. But this was generally not the case when there were "big lumbering dinosaurs knocking things down, opening up the environment" and thinning forests, Doughty says.

After dinosaurs went extinct, forest understories became about 20 percent darker. This change "reset the slate" for plants and other animals, Doughty says. And "during this time the canopy became more closed," notes Brian Atkinson, a University of Kansas paleobotanist not involved in the study. This growth would have placed evolutionary pressure on seeds to get larger again, Atkinson says, which is also reflected in fossil data. Another dip in seed size occurred with the emergence of early giant mammals and persisted until they died out.

But even though we're far from megafauna-sized, humans' influence on forests—particularly via logging—resembles that of those long-extinct giants, Doughty says. If we continue at this rate, our effect on fruit seeds might someday rival that of dinosaurs.

Jones notes that humans influence plant life in many other ways as well. "Agriculture [is] one obvious example," he says, along with "introducing exotic species, clearing forests to make suburbia, to make cities, and so on."

That complexity is one reason it could be difficult for the model to predict future fruit seed sizes, Doughty says. Another important factor to consider is the rapid pace at which human technology tends to develop in realms such as farming. Although the model provides a good analytical comparison of forest density alterations by megafauna and by humans, developments such as agriculture mean "normal ecological rules don't really apply anymore." *—Gayoung Lee*

BIOCHEMISTRY

Micro Zap

Bursts of "microlightning" could have jump-started life

EARTH, IN ITS INFANCY, offered all the elements needed to construct life. But they couldn't just assemble themselves into biology's building blocks. That process, called prebiotic synthesis, required a jolt from the outside. Lightning was an obvious suspect. So in 1952 a young American chemist named Stanley Miller filled a flask halfway with water, topped it with methane, ammonia and hydrogen to mimic the planet's early atmosphere, and then flung a miniature lightning bolt into that fertile soup.

In this landmark experiment, Miller, working with guidance from his research adviser Harold Urey, produced several amino acids out of inorganic molecules. (Amino acids combine to form proteins, which in turn combine to form living organisms.) He thus showed how life could have found its first foothold in a pool of water somewhere. But real lightning would have struck infrequently—not electrifying the same place often enough to let prebiotic synthesis unfold.

Seven decades later new research is pointing to what might be a more realistic catalyst: water itself. In *Science Advances*, Stanford University chemist Richard Zare and his colleagues report that organic molecules with carbon-nitrogen bonds can form when a simple spray of water enters a mix of atmospheric gases. The researchers essentially replicated the chemical reactions from Miller's experiment using a more reliable energy source. "Unlike lightning," Zare says, "water sprays are everywhere." Each waterfall and wave, he suggests, brought a spark of opportunity for life to emerge.

It's all because of the difference in electrical charge between water droplets. When small, negatively charged droplets come near large, positively charged ones, they sometimes discharge, producing a flash of luminescence the researchers call "microlightning." And it turns out that these interactions, like Miller's electricity, create organic by-products: in its watery, gaseous stew, Zare's team detected the amino acid glycine, as well as the nucleobase uracil—a key component of RNA.

Yifan Meng, a postdoctoral scholar at Stanford and lead author of the study, ran the physical experiment. At first, Meng recalls, he and his colleagues were interested primarily in microlightning itself. "But then we saw the clear evidence of carbon-nitrogen bond formation," he says. "This is something fundamental to biological molecules. It was really incredibly exciting."

To get life going, it wouldn't have been enough for these compounds to form once; that's why random lightning strikes were likely nonstarters. Single molecules called monomers would have needed a repetitive process to give them time to link up in long molecular chains called polymers: it takes many amino acids to make a protein and many nucleobases to make a strand of RNA.

"We need the building blocks to get concentrated somewhere," Zare says. The ideal environment for that, he argues, would have been rock crevices near water sprays. The wet-dry cycles that come with such terrain are known to foster polymerization, potentially giving rise to the complex structures that became the first single-celled organisms. David Deamer, a biophysicist at the University of California, Santa Cruz, who has worked with Zare but was not involved with this study, finds the conclusions compelling. Whether in a pond, a lake or a geyser, Deamer says, "these molecules would have accumulated wherever there was wave action or waterfalls."

This initial test did not generate all of life's prerequisites, but Meng notes that other important compounds might have been present at undetectable levels. "If we can run the experiment for longer," he says, "we should be able to detect more." Just as later elaborations on Miller's work produced a wider range of molecules, future research could confirm that microlightning supports full-blown prebiotic synthesis.

There are competing hypotheses as to how organic molecules first formed. Some experts believe they originated around deep-sea hydrothermal vents; others think they caught a ride to Earth from somewhere else in our galaxy. NASA scientists announced in January that 14 amino acids, along with all five nucleotide bases in RNA and DNA, had been found in the asteroid Bennu. Given that extraterrestrial objects routinely pummeled our planet in its early days, Deamer says, "literally, the compounds necessary for life were falling out of the sky."

No one knows what really happened when life emerged around four billion years ago. But these findings lend evidence to what Miller proposed back in the 1950s—albeit with a twist. As he told an interviewer in 1996, "nobody questioned the chemistry of the original experiment.... The chemistry was very solid." Perhaps now the spark that set that chemistry in motion is, too.

—*Cody Cottier*

PHYSICS

Knit Picking

New math describes an age-old art

IN THE CORE of a knitting machine or at the tips of a skilled knitter's needles, a strand of fiber can be transformed into anything from a delicate scarf to a bulletproof vest. But different knitting stitches tend to twist in different directions—think of a T-shirt curling at the bottom edge if the hem is cut off. The tension these stitches create can warp a two-dimensional fabric into complex 3D shapes, and predicting the final structure of a knitted project challenges crafters and manufacturers alike. Now a mathematical model published in the *Proceedings of the National Academy of Sciences USA* uses physics to untangle this issue.

Physicists are always searching for rules that govern materials' behavior, explains study lead author Lauren Niu, a physicist at Drexel University. Once rules are established, Niu says, "that's where the magic happens." Prediction becomes possible.

Niu worked with University of Pennsylvania physicist Randall D. Kamien and Geneviève Dion, founding director of Drexel University's Center for Functional Fabrics, to find a mathematical model that reliably forecasts a knitted textile's complicated shapes and folds based on the stitch pattern used.

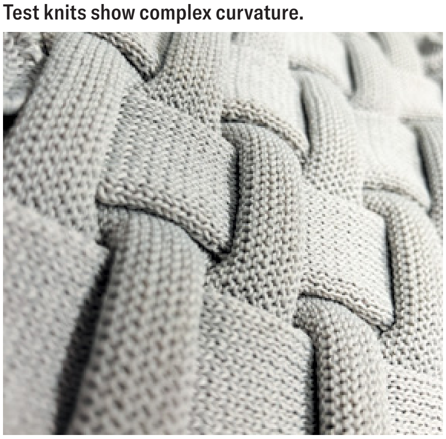
The researchers started by knitting complex patterns—including squiggles, peaks, and fabric that folded into the shape of a face—and then reverse engineered the knitted items' geometries. They realized they did not have to account for each stitch's actual shape and stretch, which would require too much computational power at the necessary scale, to foretell a textile's final form. Instead they needed to know only how each kind of stitch tended to curve the fabric.

The new model incorporates information about how stitches produce tension into an intricate mathematical construction called a Föppl–von Kármán equation. These equations describe how thin, flexible materials—such as cellular tissues and submarine hulls—behave under internal and external forces. Mapping knit stitches this way makes it possible to experiment with textile designs before physically knitting the material, Kamien says. He hopes such virtual testing will lead to more advanced, customized textiles for objects such as wearable medical devices.

"Having something that is as incredibly tunable and scalable and cheap as knitting for wearable devices is, I think, very exciting," says Stanford University mechanical engineer Cosima du Pasquier, who was not involved in the new study. Du Pasquier, who studies soft robotics that use functional textiles, would like to see how the model's predictions quantitatively line up with real-world fabrics and whether varying factors such as fabric thickness and yarn type affect that comparison.

Even without refinement, the study authors say, the model offers a practical starting point for trying new designs. "You can't capitalize on [knitting's] potential if you're still based on trial and error," Dion says. "We're starting to be able to experiment in the virtual environment." *—K. R. Callaway*

Test knits show complex curvature.



Lauren Niu

HEALTH

Fertility Physics

Wiggling sperm power a new screening test

SPERM HAVE TO WIGGLE vigorously to reach an egg, and that motion is key to a clever new fertility test. The technique, tested with bull semen and detailed in *Advanced Materials Interfaces,* harnesses physics to make fertility testing easier and more cost-effective—and, if it works for human sperm, too, it might eventually help people tackle some conception issues from home.

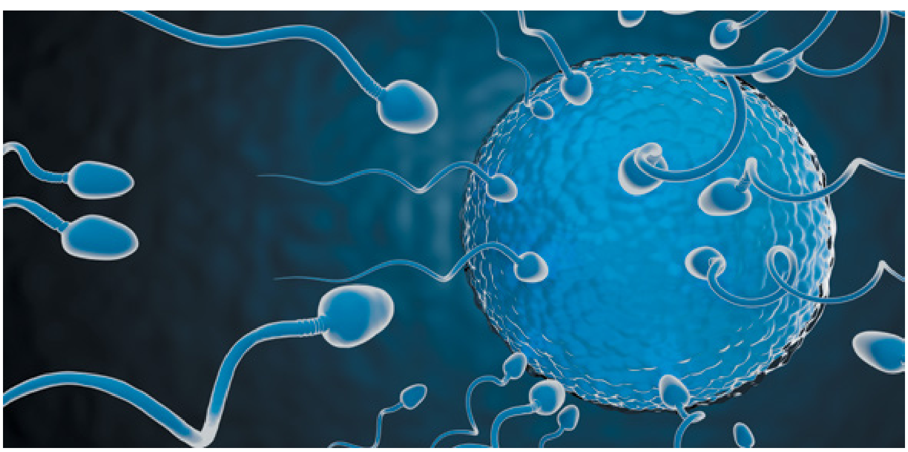
"Fifty percent of families are facing a big challenge in terms of addressing fertility," says Sushanta Mitra, a mechanical engineer at the University of Waterloo and co-author of the recent study. "Our aim is to democratize that process."

Current laboratory tests for male fertility involve examining a semen sample under a microscope. Experts check the sperm cells' liveliness, which is considered a good proxy for fertility because the gametes need to quickly swim more than 1,000 times their body length to reach an egg. But these lab tests can be expensive and time-consuming. Meanwhile at-home tests tend to be less accurate because they often only detect the presence of certain proteins in sperm rather than assessing how the cells move.

The newly described method uses basic physics to measure sperm activity without costly equipment. The researchers placed droplets of bull semen at the end of a flexible plastic strip suspended next to a water-resistant surface. Next, they moved the surface toward the drop until it made contact and then moved it back to its original position. They measured how strongly each semen droplet stuck to the surface, via weak hydrogen bonds, as it was pulled away. If many highly active sperm were wiggling around inside the fluid, the hydrogen bonds broke more quickly, disrupting the drop's surface adhesion and making it break away earlier; the livelier the sperm, the less sticky the drop. "It's exciting to be able to come up with a way to quantify sperm mobility at home," says Stanford University urologist Tony Chen, who was not involved in the study.

Mitra and his team hope to develop this technique into a cheaper, easier and more accurate home fertility test. "There is a lot of stigma around male fertility," Mitra says. Easier private testing could encourage people to evaluate semen quality more often, allowing them to check in while making lifestyle adjustments to perk up lethargic sperm, such as quitting smoking or reducing alcohol use. Such tests could also potentially be useful for breeding livestock.

The researchers' next steps will be to standardize the tests and obtain benchmarks for different types of sperm, including human and bovine. Chen says clinical trials that evaluate droplets from many different patients will also be necessary to ensure the tests work with samples that have varying pH levels, white blood cell counts and fructose concentrations. "There's more than just sperm in semen," he says. —*Joanna Thompson*



Getty Images

SCIENCE IN IMAGES

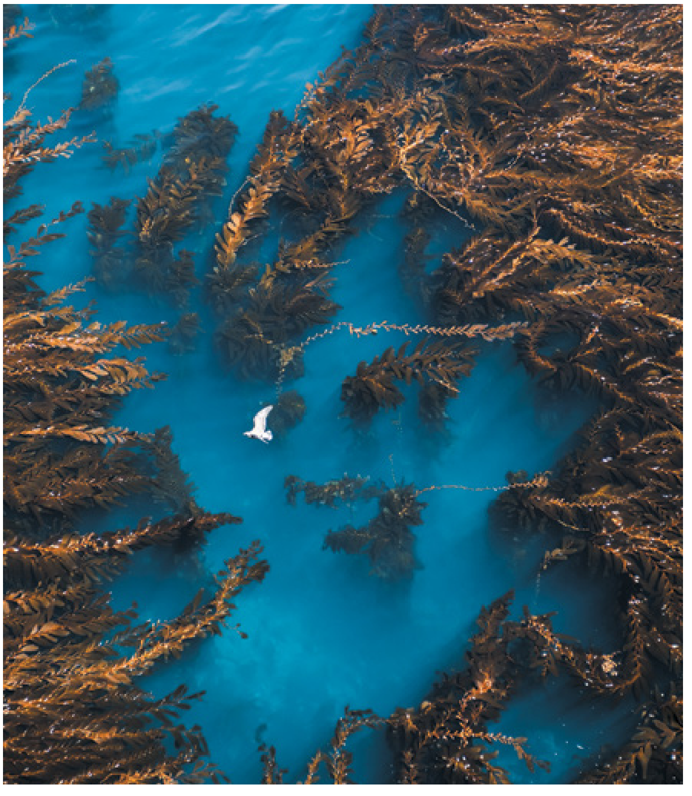
The Ocean's Veins

Can kelp evolve to survive a hotter ocean?

WHILE FREE DIVING to photograph kelp forests along the California coastline, I've viscerally felt the consequences of finiteness as a living being—the fleeting nature of a single breath, the limits of my own lungs. Kelp forests, too, have a threshold. These towering underwater jungles, which unfurl in golden ribbons with the pull of the tides, exhale life-giving oxygen into the sea, sequester carbon, shelter other organisms, buffer shorelines and remain the basis of life for many marine worlds. But along the North American coasts, heat waves, sea star wasting diseases, declining sea otter numbers and surging urchin populations have stripped away vast kelp canopies, leaving barren seascapes underneath the waves: rocky crags devoid of life except for the kelp-devouring sea urchins. In some regions, more than 90 percent of these forests have disappeared within only the past 10 years. Some Indigenous communities, who have long understood kelp's role as both refuge and lifeline, describe the plant as the ocean's "veins," carrying life through the currents. Now the pulse is fading.

And yet scientists are studying kelp not just as a casualty of climate change but as a survivor. "Diving into the kelp forest is like falling into a dream," says Sara T. Gonzalez, a researcher at the Woods Hole Oceanographic Institution. "But above all the magic of the kelp forest, what really motivated me to study kelp was its dual importance as an essential habitat for fish and invertebrates and as a valued natural resource in human society."

Gonzalez's team is tapping into the remarkable resilience written in kelp's DNA. In a recent study in the *Journal of Applied Phycology,* the researchers identified sugar kelp strains with natural genetic adaptations that help them withstand rising ocean temperatures. By crossbreeding heat-tolerant gametophytes—the microscopic



Avery Schuyler Nunn

precursors of adult kelp, as well as other algae and plants—from different species, they produced organisms that thrived under heat stress. Because gametophytes are crucial to kelp breeding, and because this resistance seems to be passed to offspring, the development could contribute to both wild kelp restoration and seaweed farming.

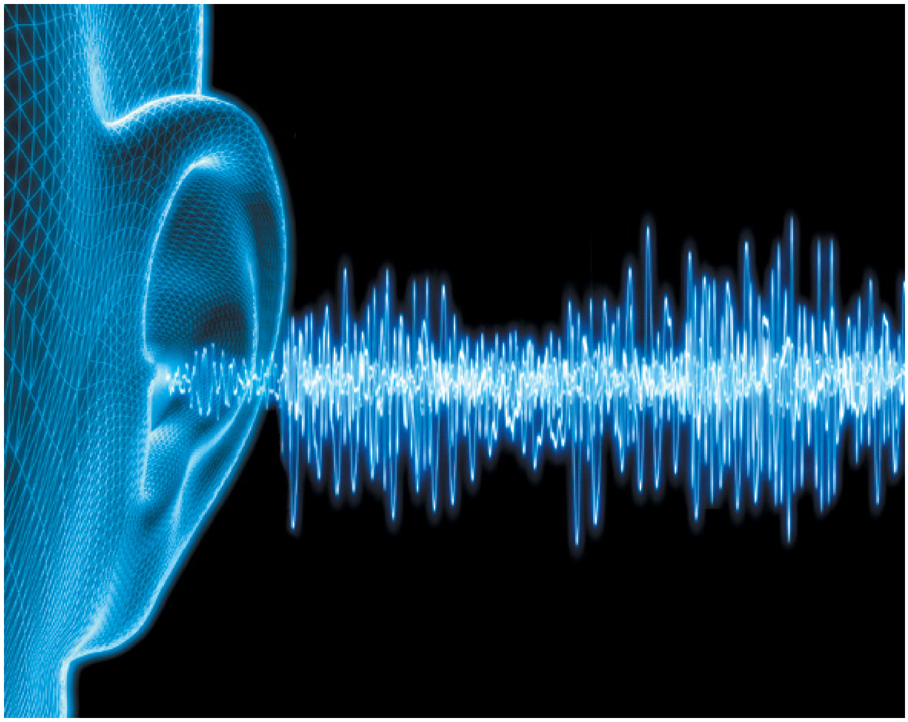
The implications of this finding go beyond one species. Across the world's oceans, from the fog-draped shores of the Pacific Northwest to the wild swells of Tasmania, kelp forests are indeed vanishing—but their own cells might hold the blueprints for their survival. "All kelps share the same life cycle," Gonzalez says, so this knowledge—of heat-hardened lineages and stress-tested spores—could ripple outward. With each discovery, scientists edge closer to restoring these forests not just in one sea but in many, coaxing back the submerged canopies that breathe life into the planet's shifting currents.

—Avery Schuyler Nunn

ACOUSTICS

Pocket of Sound

Ultrasonic beams curve and combine to produce an "audible enclave"



ARE YOU TIRED OF EARBUDS? Are headphones too heavy? "Pockets" of audible sound in otherwise quiet spots may be on their way to help.

The acoustic advance, reported in the *Proceedings of the National Academy of Sciences USA*, relies on crossing typically inaudible ultrasonic beams to create these sound pockets, or "audible enclaves." Ultrasound travels with frequencies at and above the highest edge of human hearing, about 20 kilohertz, and is often used in medicine. The study's ultrasonic beams are pitched high enough to be inaudible and can naturally bend, which lets them travel around obstacles.

In an era of podcasts and luxury sound systems, delivering audio on demand to a point in space without requiring listeners to isolate themselves from the rest of the world seems like a promising technology, says the study's senior author, Yun Jing, an acoustics expert at Pennsylvania State University. The new advance, he says, improves on "parametric" ultrasound technology that produces straight-line beams of audible sound.

"We are not relying on new concepts. But the beauty of this work is that we can combine technologies in very interesting ways," Jing says. "And there are some really interesting applications," he adds, ranging from home theaters to device-free communications.

To produce the audio enclaves, Jing's team relied on two separate ultrasound emitters just over six inches wide. Each was covered with 3D-printed metamaterials, whose tiny grooves shaped the emitters' beams to interfere with each other just so when they crossed. Then the researchers parked a dummy human head right in front of these soundless speakers.

Essentially, audio enclaves are a feat of acoustic subtraction. When one ultrasonic beam that bent to the right and another that bent to the left crossed on the far side of the dummy head, their inaudible sound waves interfered, producing a residual sound at a frequency that humans could hear at the fixed point in space. (Mathematically, a 39.5-kilohertz beam subtracted from a 40-kilohertz one, leaving behind an audible 500-hertz sound wave.) In the demonstration, the researchers played the "Hallelujah Chorus" from George Frideric Handel's *Messiah*—with the dummy head none the wiser.

The beams operated with an airborne pressure that was 1/5,200 of the U.S. Food and Drug Administration's recommendations for human exposure to ultrasound, the paper notes. But Mark Hinders, a professor of applied science at William & Mary, who was not part of the study, cautions that because ultrasound can damage hearing, the technique would require careful safety testing—which the study authors also acknowledge.

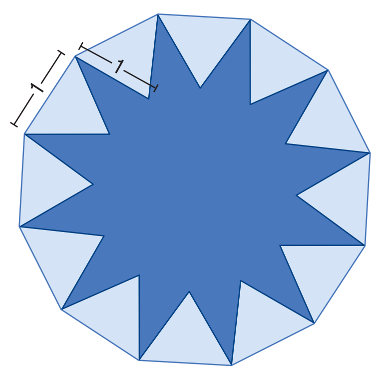
For now the prototype's sound quality isn't perfect. Jing says his team plans to use machine-learning algorithms to analyze the sounds produced by the device and improve its performance. Given the small size of the emitters, he suggests, audio enclaves in cars might be an eventual first application. *—Dan Vergano*

MATH PUZZLE

Measure the Star

By Heinrich Hemme

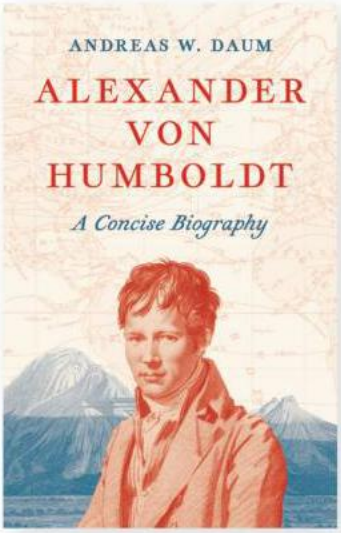
THE REGULAR DODECAGON and the blue star inside it both have a side length of 1 unit. What is the area of the star?



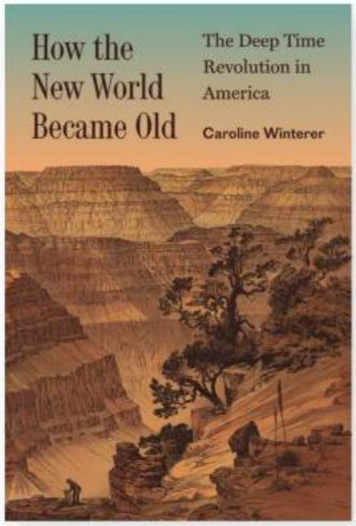
For the solution, visit www.ScientificAmerican.com/games/math-puzzles

peterschreiber.media/iStock/Getty Images Plus (*top*); *Spektrum der Wissenschaft* (*bottom*)

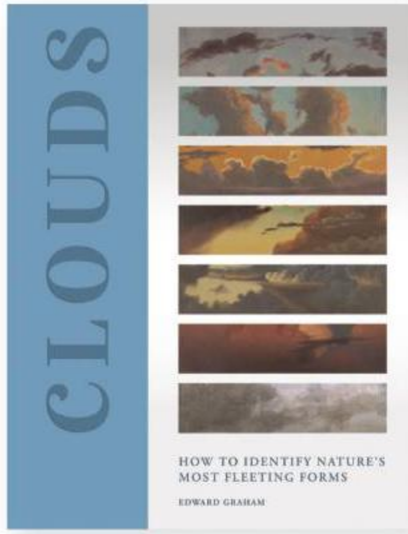
New from Princeton University Press



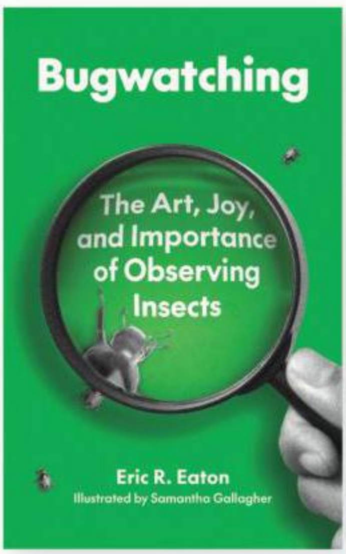
An engaging account of the life and work of the legendary polymath Alexander von Humboldt



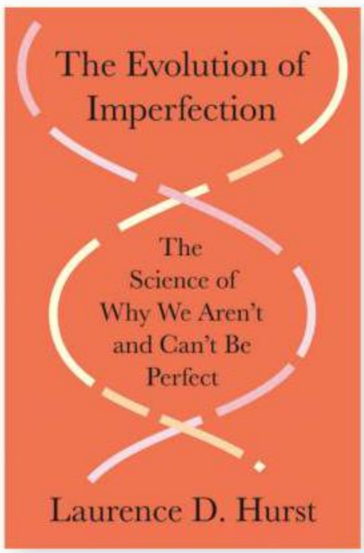
How the idea of deep time transformed how Americans see their country and themselves



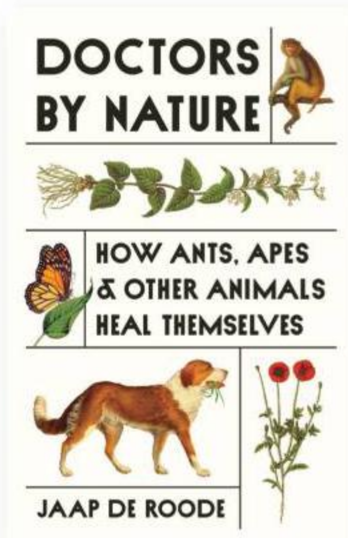
A one-of-a-kind illustrated guide to clouds, cloud formations, and the artists who painted them



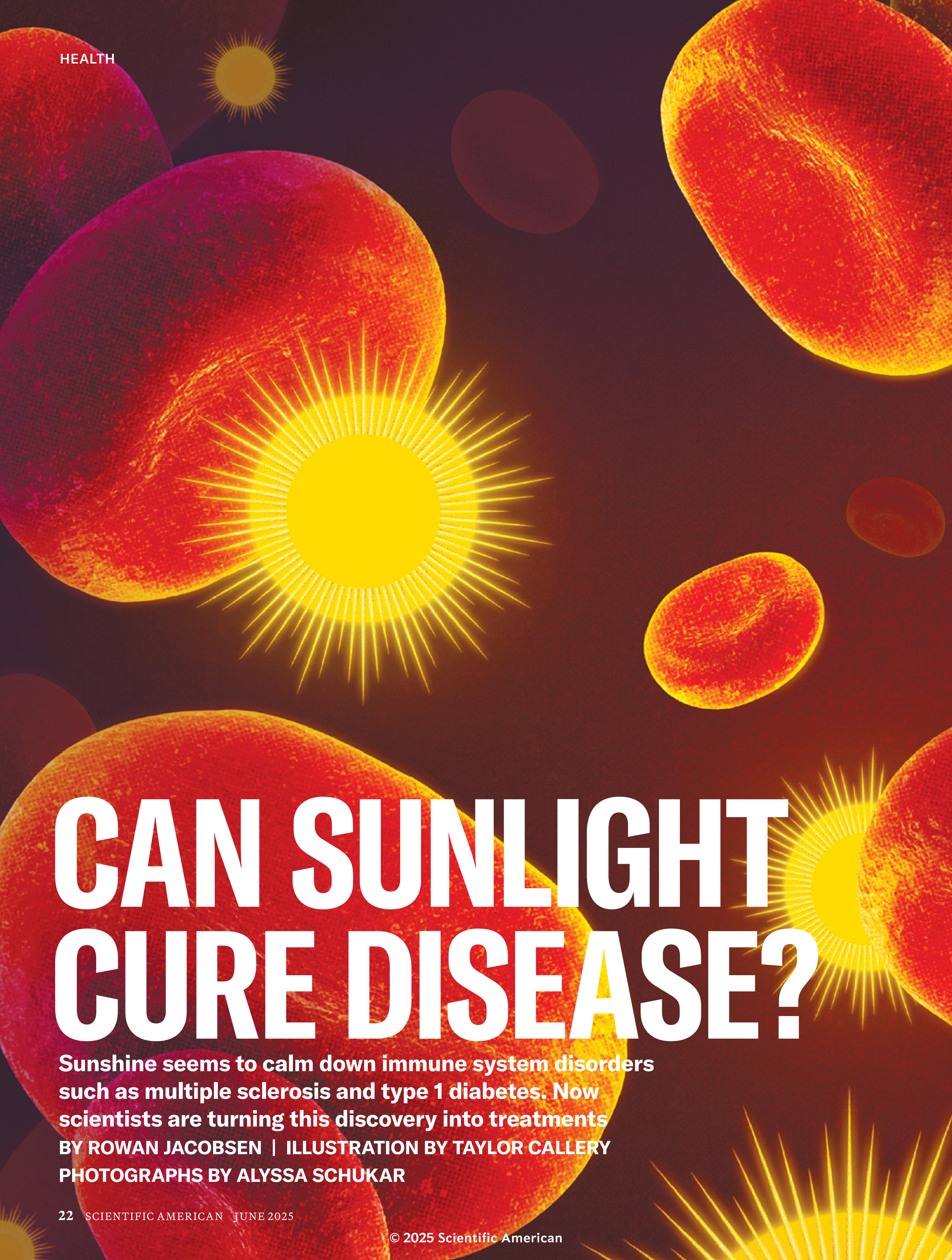
Discover the pleasures of watching insects with this fun, informative, and marvelously illustrated how-to guide



How understanding our genetic imperfections can change our view of evolution and enrich what it means to be human



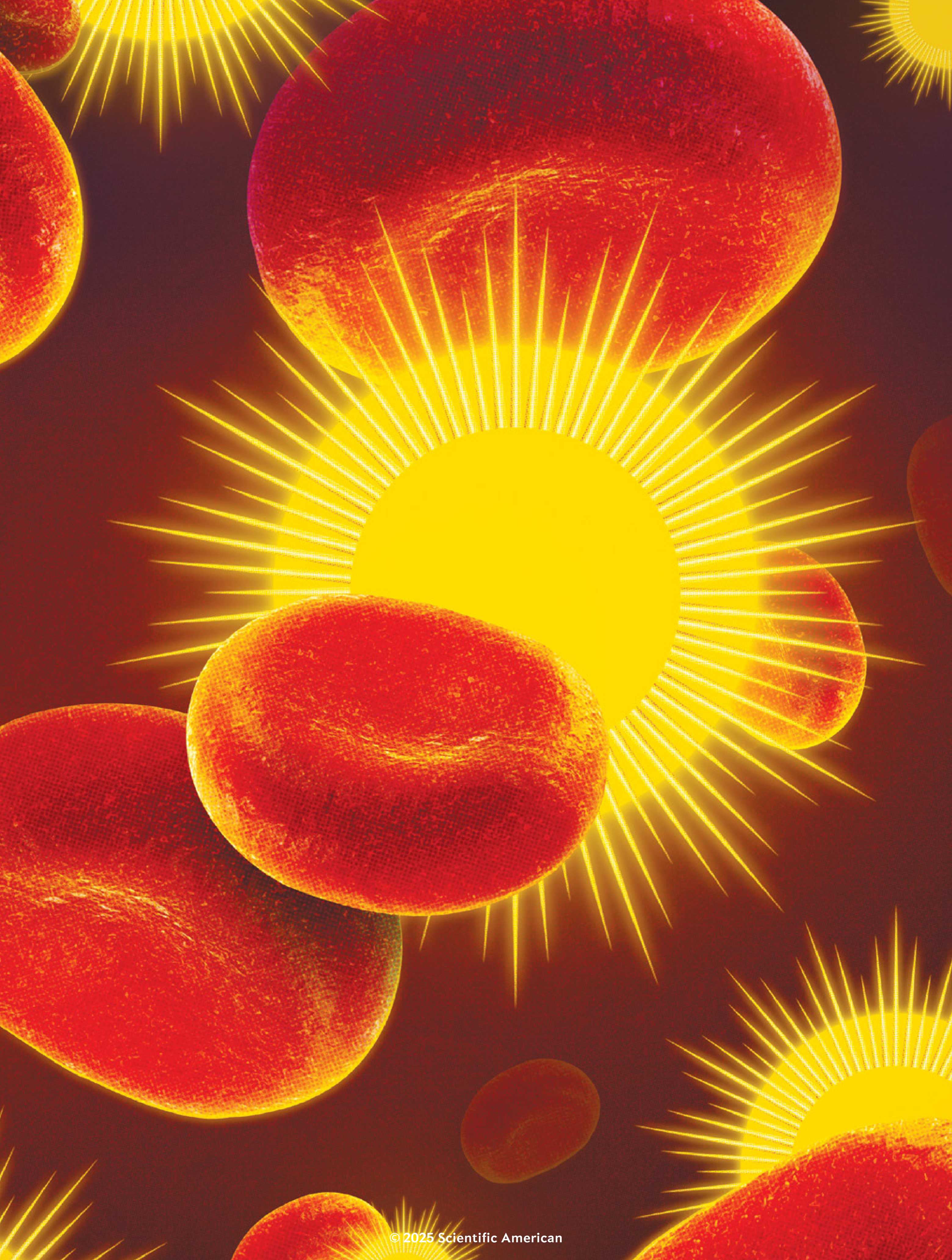
The astonishing story of how animals use medicine and what it can teach us about healing ourselves



CAN SUNLIGHT CURE DISEASE?

Sunshine seems to calm down immune system disorders such as multiple sclerosis and type 1 diabetes. Now scientists are turning this discovery into treatments

BY ROWAN JACOBSEN | ILLUSTRATION BY TAYLOR CALLERY
PHOTOGRAPHS BY ALYSSA SCHUKAR



EVERY MORNING KATHY REAGAN YOUNG STEPS OUT of the shower in her Virginia Beach home, towels off, dons a pair of protective goggles and stands nine inches from a light box the size of a small space heater. Young presses a button, and the box's bulbs begin to glow a ghostly purple. She briefly bathes her torso in the ultraviolet rays coming from the bulbs, four minutes per side. Then she goes about her day.

That Young can have an ordinary day is remarkable. In 2008 she was diagnosed with multiple sclerosis (MS), a terrible malady in which the body's own immune system attacks the sheaths that insulate the nerves, destroying them bit by bit. Symptoms begin with weakness, spasms, vision and speech problems, intense fatigue, and what Young calls "cog fog"—chronic low-grade cognitive impairment. Flare-ups can lead to periods of motor-control loss and paralysis. Young, an advocate for MS patients and creator of a popular podcast, has suffered through many such episodes. But things improved with the arrival of her light box.

Ultraviolet (UV) light boxes, which emit only a narrow bandwidth of light that is not linked to skin cancer, have been used for years in the treatment of psoriasis. Young got a prescription from her doctor, and the box was sent to her by a medical-device company called Cytokind that is hoping to expand such use to MS and other autoimmune diseases and was looking for some practical patient feedback. She tried out the device and gave them some pointers: make it smaller and easier to hold because MS often makes your hands go numb, and build in timed reminders to overcome the cog fog. Then, to her surprise, she found that her fatigue disappeared a few months after she started using it.

For years Young had been forced to rest in bed many times a day, but that stopped with what she calls her UV-fueled rebirth. "I was in a meeting, and someone said to me, 'Wow, you seem like you're pretty high energy!'" Young says. "And I guess I hadn't really thought about it. And then two days later my daughter said to me, 'Mom, what are you on?' I think we were all a little surprised by how quickly and definitively it happened." Her MS Disease Activity (MSDA) score, which rates MS severity based on the levels of key inflammatory molecules in the blood, was a 1 out of 10, the best possible score, and it has stayed low for more than a year. MS has no cure, and Young still suffers from transient pain and tingling, but the return of her vitality has made it all more bearable. "It's incredible," she says. "My friends used to invite me to things, and I'd say yes, but I always canceled because I was wiped out. Well, not anymore."

Young is one of the first people in the U.S. to test UV phototherapy as an MS treatment, but she may be at the forefront of a revolution in how we think about light and a huge class of diseases. Autoimmune diseases such as MS and type 1 diabetes occur when our natural defenses—our immune systems—viciously turn against our own bodies and organs. These illnesses are estimated to affect more than 350 million people worldwide. Treatments have been elusive.

Although only a handful of clinical trials for MS light therapy have been conducted in people, evidence from a number of medical studies now shows that UV light, the highest-energy part of the solar spectrum that reaches Earth's surface, has a surprising ability to calm an immune system that has bolted out of control. The new studies offer tantalizing hints that UV therapy

Rowan Jacobsen is a journalist and author of several books, including *Wild Chocolate* (Bloomsbury, 2024). He wrote about how brains are not needed for thinking and problem-solving in *Scientific American*'s February 2024 issue. Follow Jacobsen on X @rowanjacobsen

might also work for other autoimmune diseases such as type 1 diabetes, rheumatoid arthritis, Crohn's disease and colitis. All are more common in people who get very little sun exposure, as are maladies such as Alzheimer's and cardiovascular disease that appear to have some immune system and inflammatory connections.

Now scientists are hoping to decipher the pathways through which UV light causes the immune system to back down from its alarm state. They are tracking the way molecules in the skin such as urocanic acid and lumisterol—which can affect immune system activity—respond to a shot of photons by triggering a cascade of signals that reach every organ in the body. Advocates say this work might lead to a blockbuster drug, an Ozempic for autoimmunity.

Scientists not involved in the light research are more cautious, but they agree that something important is going on. "UV light therapy holds promise," says Annette Langer-Gould, an MS researcher and neurologist at Kaiser Permanente in Los Angeles. But she would like to see rigorous and larger trials on various diseases and a better understanding of the mechanism.

That kind of confirmation could also solve a mystery that has vexed scientists for more than a century: Why do people living in lower-light environments have such high rates of disease?

> "UV light calms inflammation in the skin, the nervous system, the pancreas and the gut. Its potential is not fully realized."
>
> —PRUE HART *KIDS RESEARCH INSTITUTE AUSTRALIA*

THE TRAIL THAT LED SCIENTISTS to the discovery of UV light's beneficial effects began with the confirmation of its dangers. In 1974 pioneering researcher Margaret L. Kripke (who would go on to found the department of immunology at MD Anderson Cancer Center in Texas) discovered that she could induce tumors in the skin of mice by exposing the rodents to UV light. But those tumors failed to grow when transferred to the skin of a different mouse. The new host's immune system quickly eliminated them. Ten times she tried, and 10 times the tumors were squelched. When she suppressed the new host's immune system with drugs, however, the tumors took hold. "That was the key!" she later recalled.

But why was the tumor able to grow in the original irradiated mouse? Was the UV light that had induced it also somehow suppressing the mouse's natural immune response? In a series of experiments, Kripke determined that UV radiation was indeed a double whammy. Not only did it damage DNA in skin cells and trigger mutations that could lead to cancer, but it also suppressed the immune system's surveillance of the skin, preventing that system from killing any budding cancers. This finding was a breakthrough in our understanding of how skin cancer develops, but it also seemed nonsensical from an evolutionary perspective. How could it possibly be beneficial for our immune system to relax in the presence of a common carcinogen?

It turns out that immune cells in our skin evolved to walk a fine line. As our primary interface with the outer world, the skin is barraged with potential stressors: heat, cold, wounds, bug bites, mysterious microbes of all kinds. For the first million years that our nonape ancestors spent under tropical African skies, solar radiation was the most common stressor of all. "It's a challenge to the body," says Prue Hart, an immunologist at the Kids Research Institute Australia who has been studying the effects of sunlight on immunity for more than 30 years. "It's the most important environmental insult we have. We evolved to cope with it."

But if the immune system had reacted to every kiss of sunlight with a full-throated attack, Hart says, we'd have lived in a constant state of inflammation, beset by rashes, hives and cutaneous autoimmune disorders. Instead the system learned to hold its fire.

In prehistoric times, this was the right approach. The damage was usually minor, the skin repaired itself, life went on. The trade-off—especially now that people live long enough for slow-growing tumors to get big and spread to other parts of the body—is that every so often a skin cancer sneaks through. One fascinating confirmation of this idea is polymorphic light eruption (PLE), a common disorder in which patients' immune systems are not suppressed by sunlight. PLE sufferers develop itchy rashes and plaques after sun exposure, but they are less likely to develop skin cancer.

The discovery of UV light's powerful impact on our immune responses launched a brand-new discipline: photoimmunology. Early investigators in this field, such as Kripke, focused on the negative effects of immunosuppression. But they soon found some upsides as well. For example, it finally explained something doctors had noticed for centuries: sunlight soothed psoriasis, a skin condition marked by painful, itchy scales. With the discovery that psoriasis was an autoimmune disease in which the immune system flays the body's own skin cells, it at last made sense. UV light—whether from the sun or a lamp—improved psoriasis by tamping down the inflammatory response.

Remarkably, the effect wasn't just local. Shining light on one patch of inflamed skin could reduce symptoms on other patches. Even more curious, people with psoriasis often suffer from other autoimmune conditions, and sometimes the phototherapy improved their other symptoms as well.

As photoimmunologists probed deeper into the mechanisms, they began to wonder whether the body's response to UV light was more than skin-deep. In the laboratory, they exposed mice to UV radiation and saw their entire immune systems pivot to anti-inflammatory states. In mice with autoimmune diseases, it improved their health. The researchers began comparing notes with epidemiologists, who were documenting signs of the same thing in human populations.

For more than a century scientists have noticed that many diseases, especially autoimmune and cardiovascular conditions, follow a latitude gradient. Once other confounding factors such as diet, exercise and socioeconomics are accounted for, rates of these diseases rise with latitude. All kinds of causes have been suggested—climate, diet, cosmic rays, something in the water—but nothing fit.

In 1940 a physician at the Medical College of Virginia named Frank Apperly showed that American states and Canadian provinces receiving more solar radiation had higher rates of skin cancer mortality but lower rates of cancer mortality overall. Skin cancer was known to be caused by sunlight, but Apperly suggested that something about the sun was also conferring protection against internal cancers. He didn't know what, but in 1980 Johns Hopkins University epidemiologists Frank and Cedric Garland, two brothers who were analyzing maps of cancer incidence produced as part of the government-led "war on cancer," noticed a strong north-south gradient for colon cancer rates and suggested in a hugely influential paper in the *International Journal of Epidemiology* that vitamin D was responsible.

Until then, vitamin D had been known mostly as the micronutrient that prevented rickets. It is produced in the skin with the aid of sunlight, and it helps to deliver calcium to bones, making them resistant to fractures. The Garlands suggested that it might do a lot more than that, and indeed, everywhere scientists looked they discovered an inverse correlation between vitamin D levels and the risk of dozens of diseases, including breast cancer, high blood pressure, diabetes, heart attack, stroke, dementia, depression, and several autoimmune disorders.

Thus began the vitamin D era. Doctors around the world recommended supplementation with this new wonder drug, and they still do for people who are seriously deficient in the substance. But as recently chronicled in this magazine, rigorous clinical trials have shown that extra D supplementation—using the vitamin as a treatment—doesn't help with any of these diseases. The maladies afflict people who take supplements and people who don't, in equal measure. Most of us get enough D from just a little sunlight or from our diets: fortified dairy products are good sources, for instance, as are fatty fish such as salmon. Whatever sunshine is doing to prevent myriad ailments, it's a lot more complicated than getting the skin to produce a little vitamin D.

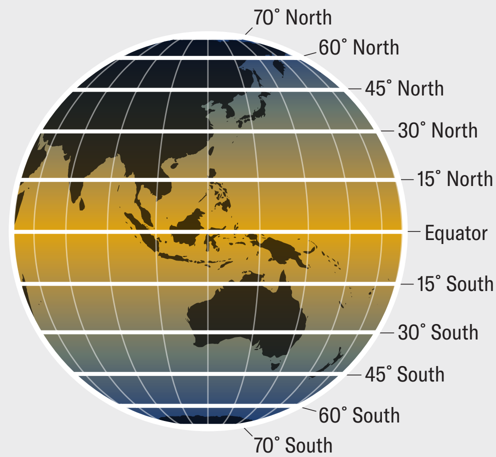
The disease with the most dramatic latitude gradient is MS. Prevalence rates are close to zero near the equator and increase by 3.64 cases on average per 100,000 people for each degree of latitude, reaching well over 100 cases per 100,000 people in northern Europe and North America. The gradient exists worldwide and has been growing stronger over time. It even shows up within individual countries, including France, the U.K., Sweden, New Zealand, Canada and the U.S.

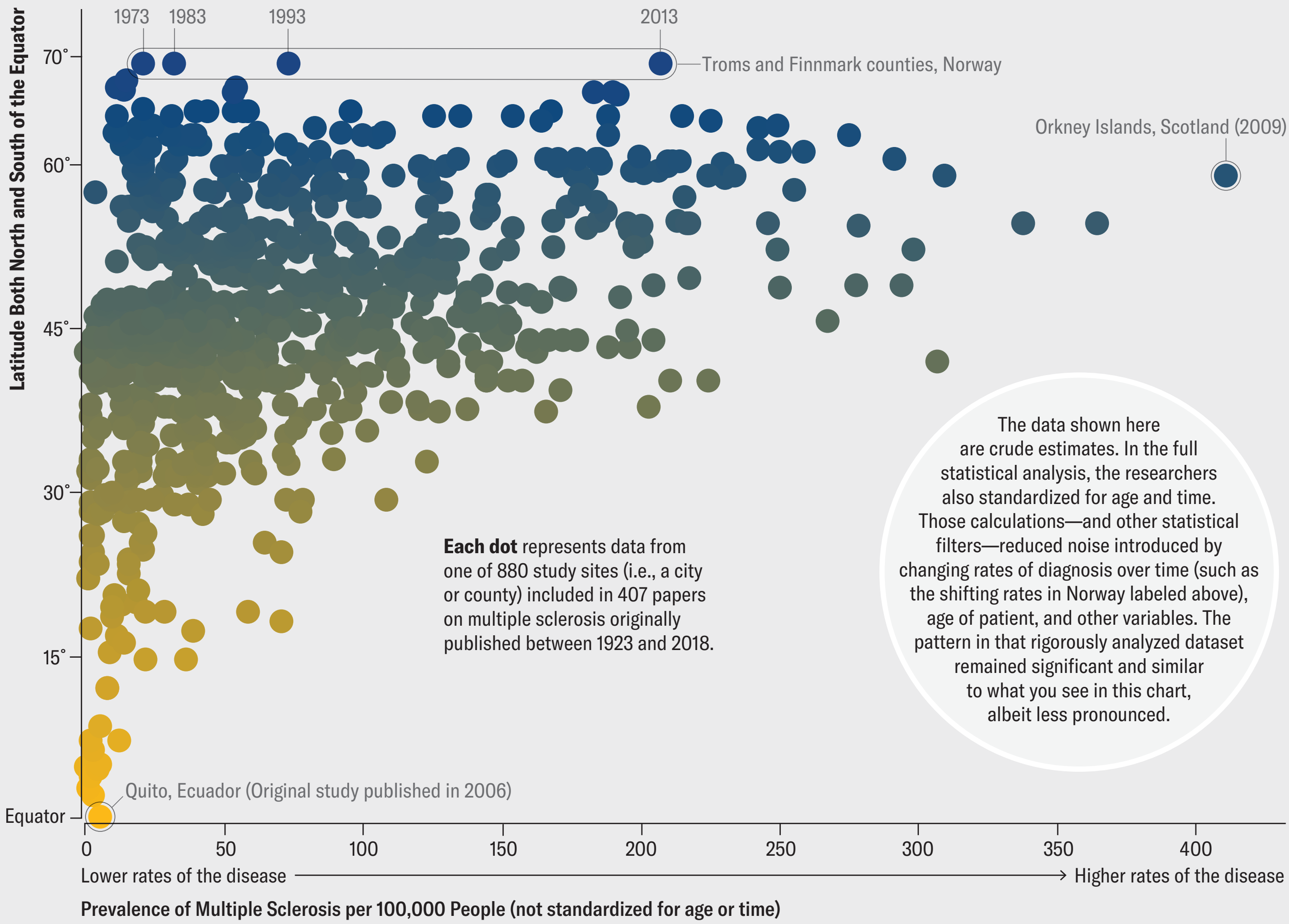
Some of the best data comes from Australia, which is one of the only countries to boast a wide range of latitudes, a relatively homogeneous population and a national health-care system with good recordkeeping. A 1981 study found that rates of MS rose from 12 per 100,000 people in tropical Townsville (19 degrees latitude) to 21 in Brisbane (27 degrees), 37 in Newcastle (33 degrees), and a whopping 76 per 100,000 people in Hobart (43 degrees). The latitude connection was reinforced in the early 2000s, when a study of various environmental factors that might contribute to MS onset found rates several times higher in Australia's higher latitudes.

At the time, says Robyn Lucas, an epidemiologist at the Australian National University who is one of the leaders of the study, many scientists assumed a lack of vitamin D at the higher latitudes was responsible. "Vitamin D was the flavor of the day. Vitamin D was cancer. Vitamin D was cardiovascular disease," she says. "Vitamin D was autoimmune disease. Vitamin D was

Shining Light on Multiple Sclerosis

One important clue about sunshine's ability to heal the body came from studies of multiple sclerosis (MS). The disease occurs when a person's immune system attacks protective sheathing around their nerves. Symptoms include difficulty walking, overall weakness, and partial or total loss of sight. MS affects one in 1,000 people worldwide. But it is much more common at higher latitudes, where there is less sunlight, and rarer near the sunny equator. After accounting for confounding factors, scientists think sunlight on skin triggers a reaction that stops wayward immune system activity.





Source: "Latitude Continues to Be Significantly Associated with the Prevalence of Multiple Sclerosis: An Updated Meta-Analysis," by Steve Simpson, Jr., et al., in *Journal of Neurology, Neurosurgery & Psychiatry*, Vol. 90, No. 11; November 2019 *(data)*

everything. And we just thought, 'Yeah, vitamin D.'"

But in 2010 Lucas read a study showing that UV treatments protected mice against MS without affecting their vitamin D levels. Mice are not always good stand-ins for people, but it was enough to make Lucas curious. "I'd just done the analysis of the vitamin D, and then this paper came out, and I thought, 'Okay, let's have a look at that,'" she says. "So I went back to our data and actually found a much stronger effect for sun exposure."

Since then, Lucas and others have found signs of sunlight's preventive effect on MS everywhere they've looked. People with the most sun damage on the back of the hand—a particularly accurate reflection of lifetime sun exposure—have just one-third the rate of MS compared with those with less. And kids who spent less than 30 minutes a day outside had twice the risk of MS compared with those who spent up to one hour outside and about five times the risk of those who averaged more than an hour outside.

Notably, observational studies like these cannot prove causation. There could be other explanations for the patterns. Perhaps people suffering the earliest symptoms of MS spend more time indoors because they're not feeling well. Maybe something else about high-latitude locations contributes to MS. So epidemiologists looked for other supporting evidence, and they found plenty. Even within the same region, MS relapse rates follow a seasonal cycle—higher in winter, when sun is scarce—and incidence rates correspond closely to birth month, being highest in people who experienced winter during their first trimester of gestation, when the brain and immune system are developing.

Additional support came from a small clinical trial by Hart. She recruited 20 patients with clinically isolated syndrome, an early-stage version of MS that eventually leads to full MS. Half the subjects received eight weeks of treatment with a narrowband-UV light box similar to the one Kathy Reagan Young uses, undergoing three sessions per week with each session lasting just a few minutes. The other half didn't get light therapy. Within a week of the first treatment, levels of inflammatory proteins in the UV group's blood dropped, and they stayed lower even after the UV sessions ended. Three months after the beginning of the trial, the UV group's disease-severity scores had fallen 13 percent, whereas the control group's had risen 14 percent. These scores correlated with the subjects' self-reported fatigue. A year after the sessions, all the subjects who didn't get UV therapy had

Graphic by Jen Christiansen

Kathy Reagan Young, who has multiple sclerosis, uses ultraviolet rays from a light box (*right*) for a few minutes every morning. Since she began treatment, her symptoms have eased notably.

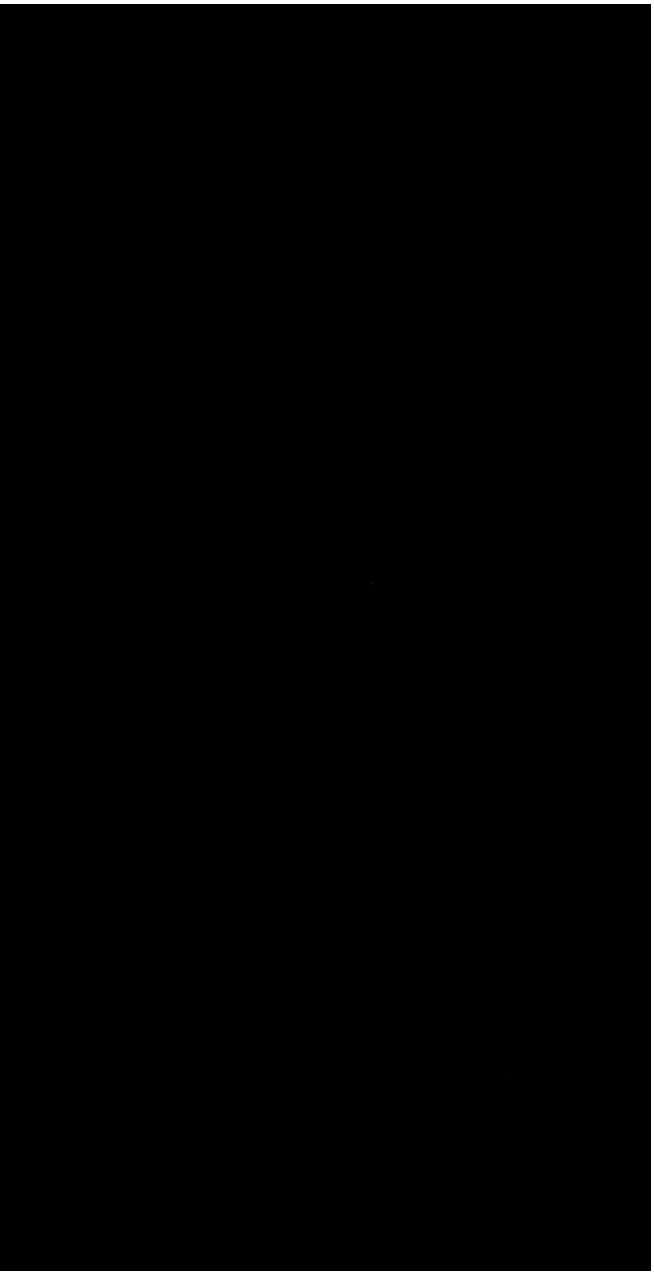
developed full-blown MS, but 30 percent of the UV group had been spared.

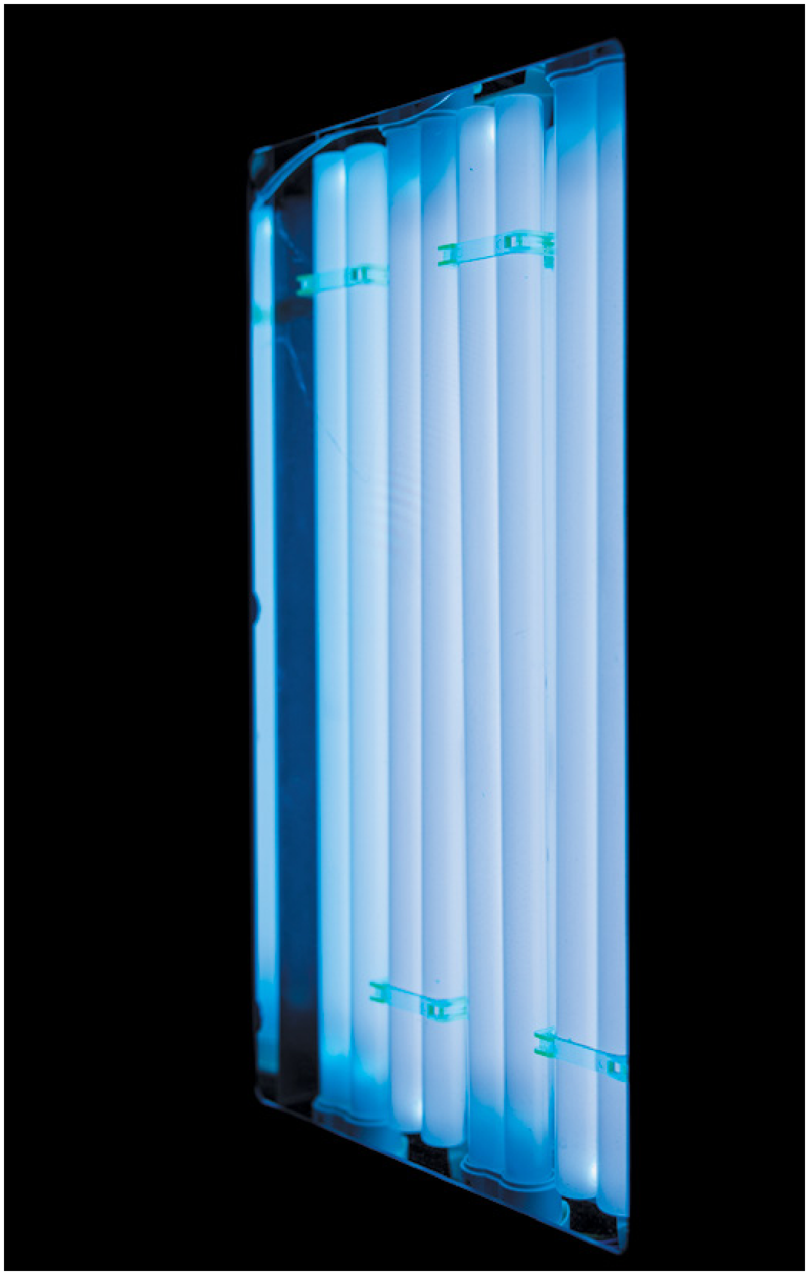
The fact that the effect lasted for months after the initial UV treatment was intriguing. Immune cells are constantly being produced in the bone marrow, and they don't last that long, so the UV hadn't just suppressed the immune cells in circulation; it had reset the system to a more tolerant state. "I think UV is part of our innate immune training," Hart says. "It reprograms subsets of innate immune cells as they evolve out of the bone marrow. They're less inflammatory and more regulatory."

The idea is similar to recent research showing that early exposure to small amounts of allergens can condition the immune system and prevent a hyperactive response later on. "You get this rebalancing," Hart says. "UV light calms inflammation in the skin. But it also then calms inflammation in the central nervous system. It'll calm inflammation in the pancreas and the gut. So I think it's not fully realized the potential it has to be a controller of body homeostasis."

The implications go well beyond MS or even autoimmune diseases. In recent years researchers have learned that many other chronic conditions also have an inflammatory component. Cardiovascular disease is caused in part by immune cells attacking and damaging the walls of blood vessels. Alzheimer's disease is connected to low-grade, smoldering inflammation in the brain. Arthritis, asthma, allergies, diabetes and even depression are thought to have inflammatory components. Something about the modern, indoor, overly hygienic lifestyle may cause our immune systems to lose their healthy set points.

Sun-exposure effects have also been found in some





other autoimmune conditions, such as type 1 diabetes, in which the immune system attacks the pancreas, disrupting insulin production. The rate of this disease is threefold higher in southern Australia than in northern Australia. In the U.S., prevalence is lowest in fall babies, who gestated over the summer. But the difference is most pronounced in northern regions and smallest in sunny spots such as Hawaii and southern California.

Taken together, Lucas says, these findings start to make a very convincing case. “We’ve now shown it in pediatric MS, we’ve shown it in Crohn’s disease, we’ve shown it in type 1 diabetes,” she says. “There’s a consistency of evidence across autoimmune diseases that have a similar immunopathology.”

GIVEN THIS CONSISTENCY of evidence, what should we do about it? Although some scientists have argued for increased sun exposure for people at high risk of an autoimmune disease, few health-care providers would ever be comfortable recommending a known carcinogen to their patients. The holy grail, in terms of widespread acceptance, would be to uncover the mysterious molecular pathway through which the skin tells the immune system to relax and then turn it into a biologic—a medication isolated from natural organisms. “What is the Ozempic for autoimmunity?” asks Cytokind co-founder John MacMahon. “Where is it going to come from? Is there something in that photoimmune cascade that can be identified?”

“We don’t know what the golden molecule is; we just know it’s not vitamin D,” Hart says. “So you take a step back and give UV, which gives the skin a chance to make whatever it is.” But a pill would be better than a light box as a treatment, MacMahon says. “People prefer pills,” he says, and doctors prefer prescribing pills, and pharmaceutical companies definitely prefer making pills.

The problem in finding "whatever it is" is that when you do shine UV light on the skin and take a peek to see what it makes, you discover a microscopic pharmacopeia. In addition to vitamin D, the skin produces melatonin, serotonin, endorphins, endocannabinoids, cortisol, oxytocin, leptin, nitric oxide, *cis*-urocanic acid, itaconate, lumisterol, tachysterol, and a dozen other vitamin D–like compounds that don't even have names yet.

Most of these molecules are hormones or neurotransmitters, and that should come as no surprise. Although many people tend to think of the skin as nothing but a barrier, it's the largest organ in the body and a vital pole of the neuroendocrine system, in constant conversation with the body and brain about how to tune the system to maintain health. It's also a major site for the immune system, stocked with body-defending—or body-attacking, if they go haywire—T cells, macrophages, neutrophils, cytokines, antimicrobial peptides, and other key players.

The way UV light stirs this many-flavored stew is both elegant and complex. For example, the body stocks the skin with a precursor to vitamin D called 7-dehydrocholesterol. When the molecule is hit with the right amount of UV energy, one of its bonds breaks, allowing its atoms to flip to a new configuration. But when hit with *more* UV energy, it flips to a different configuration known as lumisterol, which has been found in the blood in higher concentrations than vitamin D and has known anti-inflammatory and antitumor effects. The skin takes advantage of the bond-breaking power of UV radiation to produce multiple molecules, including *cis*-urocanic acid and nitric oxide, which lowers blood pressure and reduces inflammation throughout the body.

Other skin cells respond to sunlight by increasing production of pro-opiomelanocortin, a protein that is then cleaved by enzymes into three essential molecules: beta-endorphin, a neurotransmitter that causes feelings of well-being and reduces stress hormones; adrenocorticotropic hormone, which triggers the release of cortisol, a steroid that regulates stress and suppresses inflammation; and the alpha form of melanocyte-stimulating hormone, which repairs damaged cells, inhibits proinflammatory molecules and produces melanin to darken the skin.

Immunologist Scott Byrne of the University of Sydney recently discovered six novel lipids—all with names like acylcarnitine and phosphatidylethanolamine, and no, that will not be on the final test—that are produced by the skin in response to UV light and sent down to the lymph nodes under the skin, where various immune cells meet and exchange information. There they signal T cells—the powerful immune warriors that get out of control in people with MS and attack the nervous system—to stay put and stop proliferating. This pathway is separate from the one that suppresses cancer surveillance in the skin, which means it holds the promise of harnessing the good of UV radiation without the bad.

FROM OUR ARCHIVES
The Rise and Fall of Vitamin D. Christie Aschwanden; January 2024. Scientific American.com/archive

No one fully understands how this biological pachinko game sorts itself out as all these cells and signals bounce off one another, so the quest for the golden molecule will not be completed tomorrow—and is unlikely to have a simple resolution. "Isn't it naive to think one molecule is going to solve all the health conditions controlled by UV?" Hart says. A single cause would certainly be convenient, "but we evolved under the sun for millions of years. It's probably multiple."

Likewise, phototherapy itself is unlikely to deliver all the benefits of full-spectrum sunlight, but it doesn't have to. Its safety, simplicity and affordability mean all it has to do is deliver some benefit. "Phototherapy is so cheap relative to biologics," Hart says. "It's almost a no-brainer as an adjunct treatment for all these inflammatory autoimmune diseases."

That fact alone has drawn the interest of insurance companies. A UV light box costs about $2,000, whereas adalimumab (Humira), a leading biologic drug for various autoimmune diseases, lists for $80,000 a year and must be taken for life. Inspired by that math, along with clinical trials showing phototherapy to be as effective as some medications with fewer side effects, Kaiser Permanente provided 2,200 of its psoriasis patients with free at-home UV light boxes as an experiment. Fewer than a third of them went on to use biologics. Kaiser Permanente now lists at-home UV as a recommended treatment for psoriasis.

But Langer-Gould, the MS expert at Kaiser Permanente, says that although she'd be interested to see whether the light boxes the insurer uses for psoriasis would be helpful for MS, it's too soon to make that leap. "Hart's data are very encouraging," she says. "But the current evidence is not enough to conclude a definitive treatment effect and recommend widespread use. We need at least one more study." That study would have to be a clinical trial large enough to show a significant improvement in patients' underlying conditions. Cytokind is currently pursuing such a study, but the results are probably still years away.

In the meantime, the flexibility of phototherapy will allow Young and other converts to fashion their own healing protocols—independence that becomes all the more precious when you have a debilitating disease. "MS robs you of so much," Young says. "You can't get out of bed, can't go to work, can't clean your house, can't get your groceries. You've got to find rides just to go to the doctor." For now, at least, she has traded all that for busy days of weight training, yoga, charity work, live chats, guided meditations—and a few minutes of UV light every morning. "It's just so empowering," she says. "To find a treatment that lets you actually take care of yourself is kind of amazing." ●

Reporting for this piece was supported by the Nova Institute for Health.

Young strolls in the sunshine near her Virginia home. Her ultraviolet therapy has let her resume her daily activities and minimized many difficulties and pains created by her multiple sclerosis.

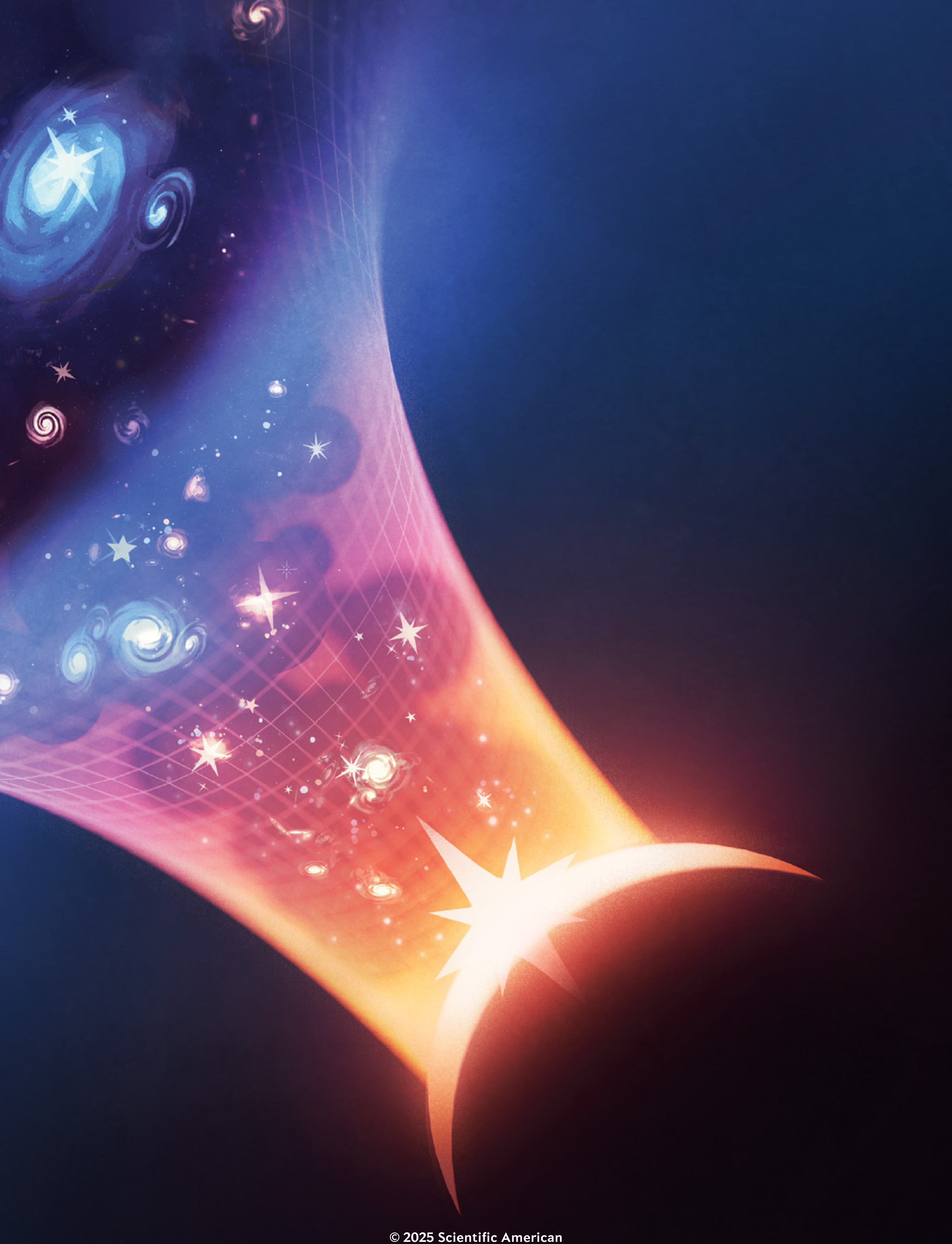
COSMOLOGY

Cosmic Dawn

A new generation of telescopes and experiments could peer back to the earliest epochs of the universe's history

BY REBECCA BOYLE

ILLUSTRATIONS BY OLENA SHMAHALO



ON WHAT MIGHT HAVE BEEN THE PROUDEST DAY of Jack Burns's long career in astronomy, he was sitting on a beach. Orbital dynamics and launch schedules wait for no one, and Burns couldn't move his long-planned family trip. So in February 2024, while on vacation in Maui celebrating his successful cancer treatment the prior year, Burns listened to a live feed from the mission control of private aerospace company Intuitive Machines. The firm's Odysseus lander was about to become the first commercial spacecraft to touch down on the moon.

It was carrying an instrument for a project Burns had helped design: an array of four antennas designed to listen for radio waves at the lunar surface—a first small step toward tuning in to the earliest days of the universe. As Burns listened, Odysseus landed on the moon's surface—and then tipped over. Burns's instrument, the Radio wave Observation at the Lunar Surface of the photoElectron Sheath (ROLSES) experiment, captured data for 25 minutes. "It was still functional enough for us to deploy our antennas and get some data, so we can declare that the epoch of radio astronomy on the moon has begun," Burns recalled during a video chat, pumping his fists in the air. "My students say, 'Oh, this is disappointing,' and I say, 'You're right, but look at it from my perspective. Look how long it's taken us to get there.'"

The short-lived experiment was a career highlight for Burns, now a professor emeritus at the University of Colorado Boulder, and it was a boon for a new generation of radio-astronomy cosmologists now taking the lead. Analyzing those few minutes' worth of data could help scientists eventually design a full lunar radio observatory. Such a mission could let researchers peer through all the light there is, all the way back to the universe's very first light, to the time before galaxies or stars, before even the first molecules—to a phase called the dark ages, when there was nothing but electrons spinning around atoms of hydrogen.

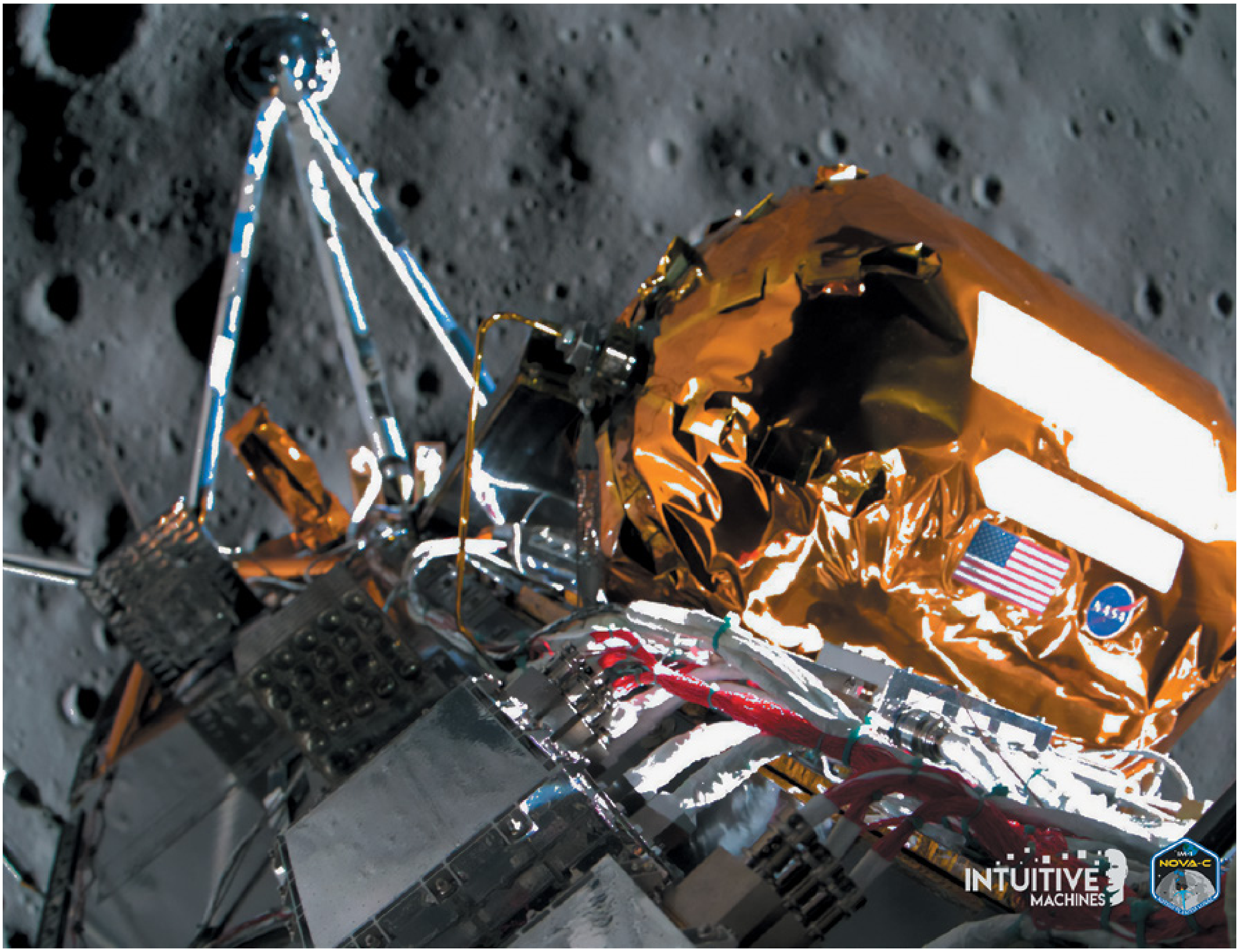
The end of the cosmic dark ages and the start of cosmic dawn mark the time when the universe as we know it began to take shape. We can't see back to this cosmic era. But by detecting faint, long-wavelength radiation from the wriggling atoms of this epoch, we may be able to develop a more detailed picture of why our universe looks the way it does today and how it got that way.

ROLSES was among the first forays into this new frontier. A NASA-funded project called the Lunar Surface Electromagnetics Experiment, which is set to land on the moon in 2026 onboard a different commercial lunar lander, will also conduct low-frequency radio astronomy to investigate these questions. These two missions will join a dozen others based in Earth's most austere reaches, all aimed at studying this lightless era of the universe, the cosmic dark ages, and the ushering in of the cosmic dawn.

"From the time before there even are galaxies, the blunt answer is that currently we can do almost nothing," says Sarah Bosman, an early-career researcher studying the cosmic dawn, who leads a team at the University of Heidelberg in Germany. But that all stands to change with the new generation of experiments starting up. "There is an enormous amount of money going into observatories to see this; we have talked about this for 50 years now."

EVERYTHING STARTED in the tremendous burst of energy known as the big bang. Within a few seconds the universe cooled enough for the first protons, neutrons, electrons and photons to spark into existence, and within a few minutes those building blocks came

Rebecca Boyle is a *Scientific American* contributor and an award-winning freelance journalist in Colorado. Her 2024 book, *Our Moon: How Earth's Celestial Companion Transformed the Planet, Guided Evolution, and Made Us Who We Are* (Random House), explores Earth's relation with its satellite.



Intuitive Machines's Odysseus lander took this snapshot of the moon as it descended toward the surface.

together to form the first nuclei of hydrogen and helium. After about 380,000 years, the universe was sufficiently cool for those protons and neutrons to grab free-flying electrons and form the first electrically neutral atoms. For the first time, photons stopped colliding with free electrons and were able to flow through the universe. This process, confusingly called recombination—it was actually the first true combination of atomic components—released the cosmic microwave background (CMB) light that pervades all of space. The most detailed map of this background is from the Planck satellite, a European space observatory that launched in 2009 to study this light.

In the glow of the CMB, the universe kept filling with neutral atoms. With no stars to shine through the gas, darkness persisted for the next 50 million years. Hydrogen atoms absorbed all photons that remained from the big bang, shrouding the universe in fog. Dark matter invisibly clumped together during these cosmic dark ages, and gravity quietly shepherded matter to form the superstructure of the universe. While gravity was at work, random fluctuations in the density of matter were already charting the universe's course.

Sometime between 50 million and 100 million years ago, gravity drew hydrogen atoms together and ignited the first stars. Their sparkling ultraviolet light recharged the neutral gas, kicking electrons out of atoms and giving the atomic nuclei positive charges. This end to the dark ages marked the beginning of the cosmic dawn—another era we are just now able to study.

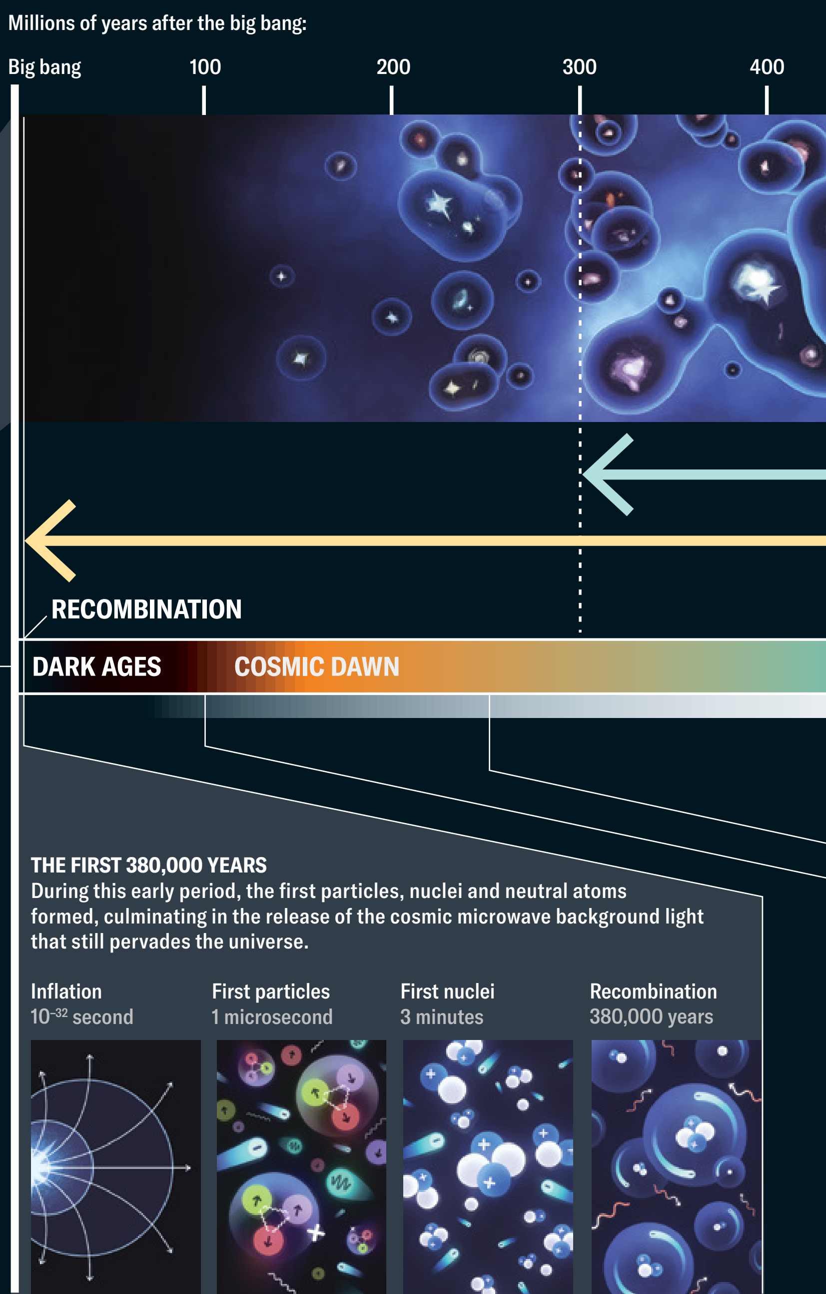
At some point during the dawn, the first stars shone brightly enough to prevent hydrogen nuclei from recombining with electrons into neutral atoms, ending the dark ages for good. This change is called the epoch of reionization, and it is when the universe became transparent to light again. Eventually during this period—we don't know exactly when or how it happened—gravity swept the first stars into the first galaxies and galaxy clusters. Now the light from those earliest galaxies is seeping into the infrared instruments of the James Webb Space Telescope (JWST), surprising everyone by showing that the early universe was dramatically brighter than anyone expected. Those early, bright objects might shine some figurative light on the epoch of reionization itself.

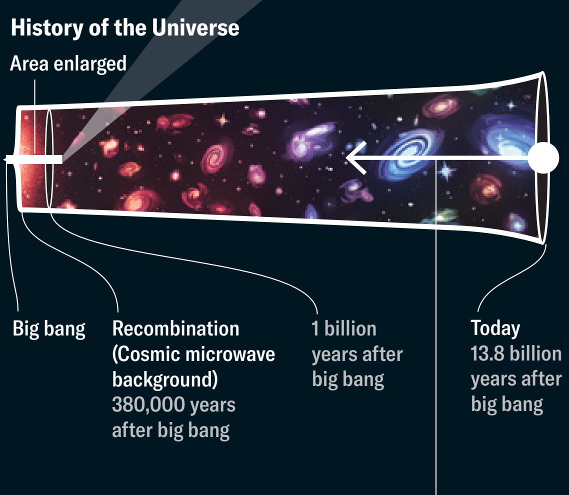
"With Planck data, we have this picture of the densities of the universe 380,000 years after the big bang. And we have a picture later of all the galaxies from the Sloan Digital Sky Survey, the Dark Energy Survey, James Webb, and other stuff. But we don't have any-

Intuitive Machines

Early Cosmic History

Scientists think the universe began with a big bang, followed by a period of rapid expansion called inflation. About a microsecond after the big bang, fundamental particles sprang into being, and after three minutes, quarks combined to form protons. But it wasn't until 380,000 years later that the hot, dense universe had cooled enough for protons to join electrons to form neutral atoms—an event called recombination. For a long time, the universe remained dark in an era called the cosmic dark ages. The first stars and then the first galaxies appeared when the universe was more than 100 million years old, heralding the start of the cosmic dawn. The end of this epoch is marked by a new stage for the universe named reionization, when the light from the early stars was bright enough to knock electrons loose from atoms, transforming the early neutral atoms into charged ions. Scientists are beginning to develop telescopes that can peer back to these ancient eras.





Because light takes time to travel through space, looking farther out in space corresponds to looking further back in time.

thing between them," says Charlotte Mason, an astrophysicist at the University of Copenhagen.

The origin of the cosmos is a story we can unravel through gravity and particle physics, but what we are missing, and need to understand, is how the first starlight changed the course of the entire universe.

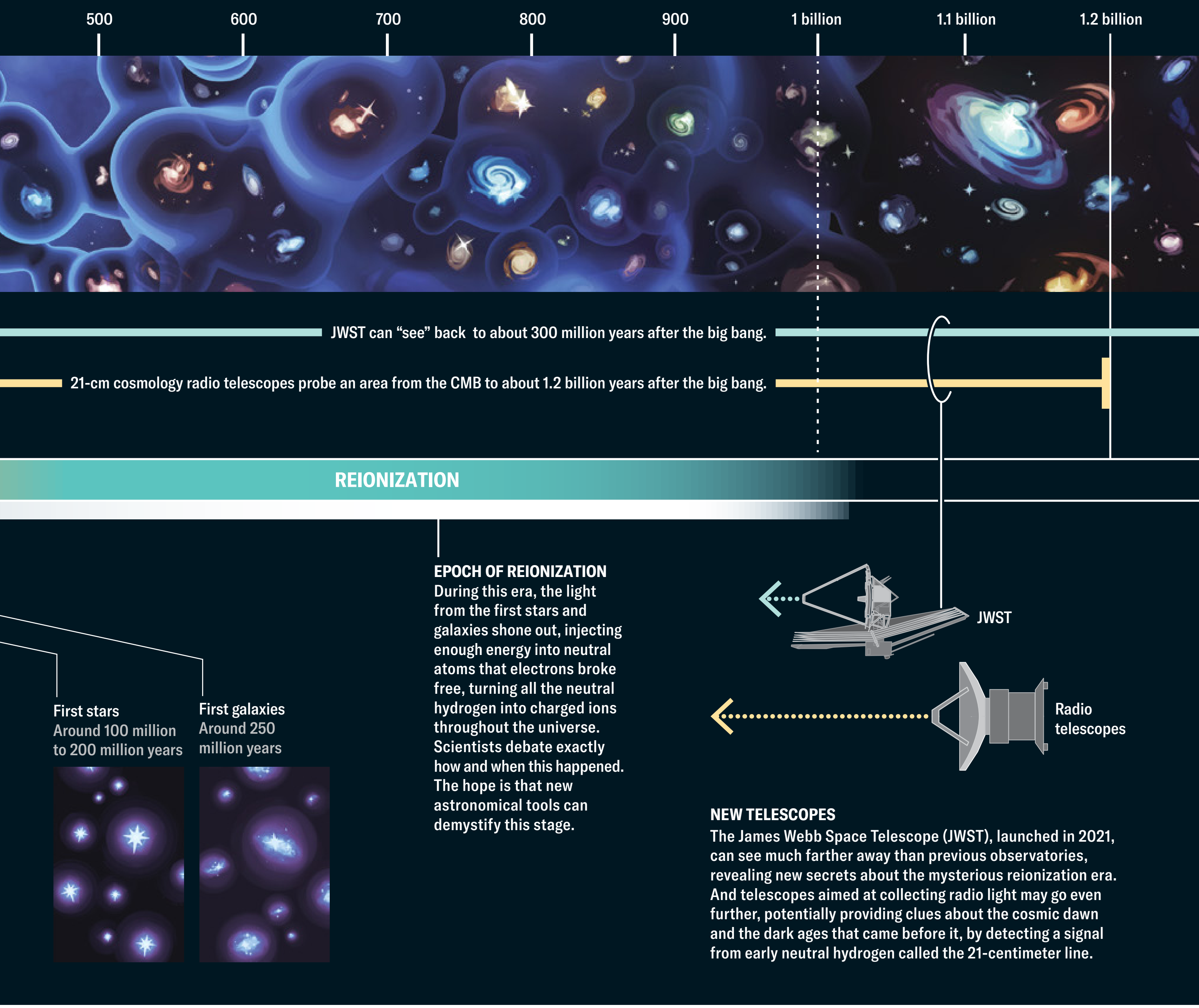
Scientists have so many open questions. Did galaxies churn out stars in furious bursts? Was there a period of "disco reionization" when the universe pulsed bright and then dark again in a continual pattern? Did reionization happen just once or maybe twice? Did it happen on a local scale in certain cosmic regions, or did everything light up everywhere all at once?

"There is so much that we don't know about galaxy formation," says Sangeeta Malhotra, an astrophysicist at the NASA Goddard Space Flight Center. "My motto as an observer is that everything that can happen that is permitted to happen will happen."

BECAUSE OF THE ACCELERATING expansion of the universe, astronomers can infer that objects at great distances are very far back in time. The stretching of their light into longer wavelengths, known as redshift, tells us their ages.

But when scientists peer very far back, they find conundrums. JWST observations of the distant past are at odds with theoretical physics in many ways. One surprising discrepancy involves the timeline of the cosmic dark ages, the epoch of reionization and the cosmic dawn.

In 2022 Bosman and her colleagues used 67 quasars



Source: Nivedita Mahesh (*scientific reviewer*)

(galaxies with bright, supermassive black holes at their centers) to determine that the cosmic dawn ended—that is, reionization was complete—1.1 billion years after the big bang, 200 million years later than previously thought. The timing of this event had been a controversy for more than two decades. But then JWST came on the scene. According to JWST observations from May 2024, ultrabright, huge galaxies were blazing brilliantly 750 million years before the end of the cosmic dawn. If they were shining brightly enough to reionize all the neutral gas, why did that process—reionization—take as long as it apparently did?

The current record holder for the oldest known galaxy is a mammoth object found at a redshift of 14.18, which means we see it as it appeared just 300 million years after the big bang. The galaxy is called JADES-GS-z14-0, named for the JWST search program that found it. When this galaxy first shone forth, the universe was just 2 percent of its current age, and the end of reionization was still hundreds of millions of years in the future.

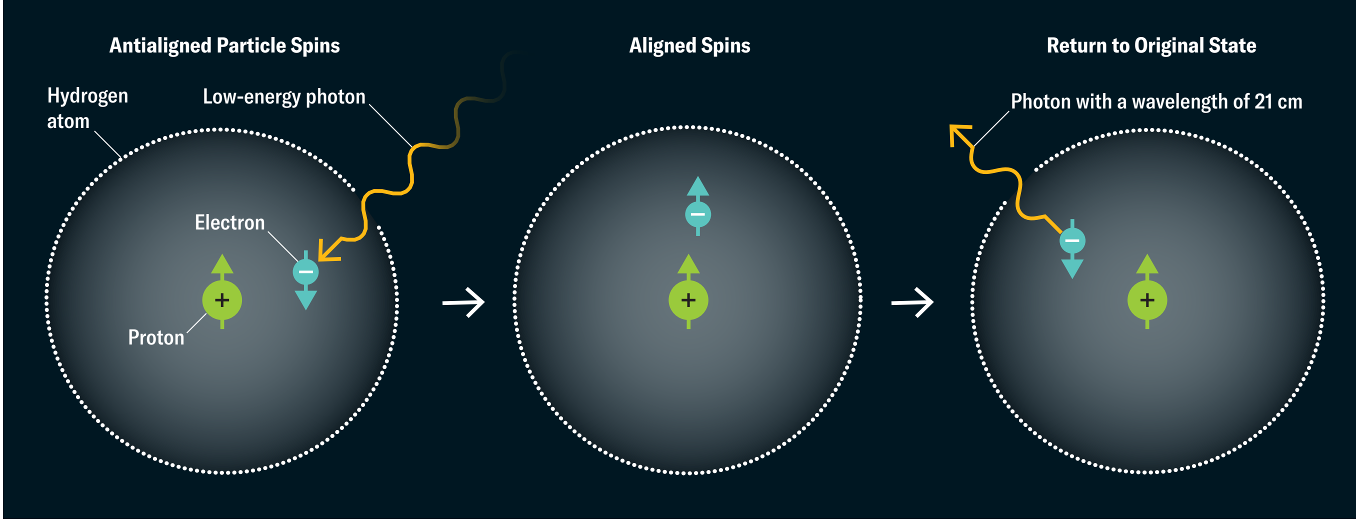
"These bright galaxies should have been able to finish reionization earlier than they did," Bosman says. Researchers are now unsure which is off: our measurements of stellar brightness or our theories. If it's the latter, new models will be necessary to explain the ultrabright galaxies. The next few years of JWST data releases are likely to raise even more questions.

Some astrophysicists argue that a small number of incredibly luminous galaxies could have reionized the

Graphic by Olena Shmahalo and Jen Christiansen

An Ancient Signal from Hydrogen

During the cosmic dark ages after the big bang, the universe was filled with neutral hydrogen atoms. These atoms released light because of a trick of atomic physics. Electrons and protons in an atom prefer to orient their spins in opposite directions. If an electron absorbs energy from light, it will use this boost to flip its spin. When it falls back into misalignment, it will release energy in the form of a photon with a wavelength of 21 centimeters, which scientists now aim to detect.



gas, letting light shine through the universe. Or it could have been the work of multitudes of faint galaxies that we can't see now and maybe never will, says Jackie Champagne, a postdoctoral researcher at the University of Arizona who studies the epoch of reionization. The projects aiming to investigate the cosmic dark ages and cosmic dawn will try to find the oldest, earliest objects that put light into the universe.

"As we get closer to seeing cosmic dawn, we should be seeing smaller galaxies, fainter galaxies, and fewer of them," Champagne says. "We should be reaching the limit where there just are no more galaxies to see."

STUDIES OF GALAXIES are one way to answer questions about the first light in the universe. Another is to study what was there before the galaxies formed: the neutral hydrogen gas before it was reionized. Because this ancient atomic hydrogen existed during the dark ages, we can't see it directly. But there are ways to map its presence.

Malhotra has been studying galaxies that emit light in a certain wavelength that is characteristic of the recombination of hydrogen—the moment when neutral atoms formed. This wavelength is visible in a galaxy's light spectrum in the form of a bump called the Lyman-alpha spectral line (the galaxies are called Lyman-alpha emitters). Surveys of these objects can help astronomers build a map of the cosmic dawn, but that requires studying a large patch of sky in the right wavelengths of light, Malhotra says. NASA's Nancy Grace Roman Space Telescope, planned to launch in May 2027, should finally deliver this information. "It's beautiful," Malhotra says. "With Roman, we are really looking forward to great science."

Meanwhile 10 experiments being planned on Earth and at least two designed for the moon will also attempt to study the time of darkness. These experiments must be set up in austere environments, such as on a floating platform in the middle of a lake, in the Arctic or on the moon, where FM radio signals can't interfere with observations.

Cynthia Chiang, an experimental cosmologist at McGill, works on small observatories—roughly the size of a dining room table—that can listen to the faint universe. In her current project, Chiang deploys these antennas in the high Canadian Arctic, which is free of broadcast signals and other radio pollution. Whereas radio telescopes such as the Very Large Array and the Square Kilometer Array are built to produce images, Chiang's work is more like a car radio tuner that can scan all stations at once. ROLSES had similar aims, and studying the moon's environment in radio frequencies can help astronomers determine how natural and human-generated activity could interfere with later, more sensitive operations. The experiments will help unveil some of the early history of the universe, Chiang says.

"If you think about it in terms of a human lifetime, the period of the first stars corresponds to the age of a toddler," Chiang says. Although humans change slightly in appearance as we grow, in early childhood many of us already resembled the adults we would eventually become. In a similar way, astronomers can use early cosmic history to make inferences about how the universe came to be its present-day self, Chiang says.

BUT LOOKING FOR TODDLER pictures of the universe is akin to looking for a candle flame inside the sun. The information is outshone by everything else. To see it,

Graphic by Jen Christiansen

the latest generation of dark ages astronomy experiments are relying on a trick of atomic physics.

When the universe was full of neutral hydrogen, it was opaque because the atoms couldn't interact with photons. The hydrogen could simply float through space, but photons from the big bang were essentially trapped among them. Yet there was still light we can perceive because hydrogen atoms naturally glow on their own. An atom's spinning electron slightly prefers to orient itself perpendicular to the nucleus's spinning proton. If those alignments flip, the energy in the atom changes slightly, and the atom will eject that energy by emitting a photon with a wavelength of 21 centimeters. Astronomers try to glimpse this transition by searching for radio signals that correspond to that 21-cm-long light wave. To our instruments, it's the same as a 1,420-megahertz transmission.

This faint glow from the spin transition is a rare sight; it fades in the light of the first stars. But the universe is old and large, so there are many places to look for it. Over time the 21-cm wavelength gets stretched out, depending on how long it traveled through the expanding universe before reaching our radio dishes. This means 21-cm photons will have longer wavelengths when we see them on Earth or the moon, and these wavelengths give us information about when the light was produced. If astronomers can map this spin-flip light, similar to how they have mapped the cosmic microwave background, they can create something like a time-lapse movie of the universe from the beginning until now.

"If you imagine listening to your car radio and scanning all stations, you are listening to how loud it is overall," Chiang says. "The signal we are looking for is a handful of stations in the middle that are a little bit quieter than the rest."

The behavior of the 21-cm signal is related to the characteristics of the first stars, which reionized the hydrogen and let there be light. "We will never be able to observe the individual stars themselves, but we will be able to see their properties and what was fueling them," Chiang says.

So far no one has definitively seen back to the cosmic dark ages, although one experiment claimed to detect the 21-cm hydrogen line from 180 million years after the big bang. In 2018 the Experiment to Detect the Global Epoch of Reionization Signature project reported a signal suggesting that either the hydrogen gas permeating the early universe was cooler than expected or the background radiation was much stronger than expected.

Follow-up experiments have not replicated that finding, but radio astronomers around the world are preparing for a new wave of searches. Observatories such as the Low-Frequency Array, the Hydrogen Epoch of Reionization Array, the Murchison Widefield Array and the Large-Aperture Experiment to Detect the Dark Ages are producing the first outlines of a 21-cm map. Soon the Square Kilometer Array, under construction in Australia and South Africa, will be able to scan the entire cosmos for the 21-cm signal. Still, there is much work to do to disentangle the faint echo of a spinning electron from the noise of the universe, Malhotra cautions. "The noise between us and the photons has to be overcome," she says. "That kind of astronomy we don't completely understand."

THE BEST HOPE scientists have of understanding the cosmic dark ages is to get away from Earth's radio noise entirely and go to the moon—the ultimate goal for Burns, who has hoped to glimpse this epoch of the cosmos from that vantage point for his entire career.

From the moon, astronomers can create a pristine map of the universe's early neutral hydrogen. Measurements of the depth and width of the hydrogen signal will reveal the nature of the first stars: how massive they were, how much ultraviolet light they produced, how hot they were, and more. We may never see them directly, but we could see their environments and try to understand what they must have been like, Burns says. "Just from the spectrum, we'll be able to infer all those properties about the cosmic dawn," he says.

The Lunar Surface Electromagnetics Experiment, nicknamed LuSEE-Night, will also join the hunt when it launches sometime in 2026. The spacecraft, which is being built by NASA and the U.S. Department of Energy, will ride to the moon onboard Firefly Aerospace's Blue Ghost commercial lander. Once in place on the moon's far side, LuSEE-Night will use an enormous battery to survive the frigid lunar night—a prime time to listen to the distant dance of ancient electrons. If the mission succeeds, it will be the first lunar cosmology experiment—but not the last, Burns says.

He envisions a full-size cosmology telescope on the far side of the moon, built using lunar soil. One proposal, called FarView, calls for constructing networked antennas on the moon by extracting metals and elements such as oxygen from moon dust and then manufacturing parts on-site. On the far side, the moon itself blocks Earth's radio cacophony, allowing those faint 21-cm photons to stand out clearly through the noise.

For veterans like Burns, these advances have been a long time coming. Burns gave his first presentation about a lunar radio telescope in 1984 at a lunar and planetary science conference in Houston. "I never would have thought that it would take 40 years before this would be realized. I feel lucky that I am seeing it in my lifetime," he says.

But Burns is also glad to be passing the torch. "This is where it starts: we will pick up hints, collect data, refine our instruments," he says. Over the coming years scientists will fly new missions to the moon, gain more experience and eventually install the instrument of his dreams. "We will eventually crack it," he says. "Or at least somebody will." Burns takes hope from the young scientists joining the quest now—the students, postdocs and newly minted professors who will lead the coming efforts. "They're the ones who are going to make this happen," he says. "It's thrilling to see them understand the sense of discovery that is before them." ■

FROM OUR ARCHIVES
The New Race to the Moon. Rebecca Boyle; August 2022. ScientificAmerican.com/archive

CLIMATE

Refreezing the

Researchers are trying to rebuild the disappearing sea ice above the Arctic Circle so it can reflect the sun's warming rays

BY ALEC LUHN | PHOTOGRAPHS BY TAYLOR ROADES

A team with Real Ice prepares to drill through sea ice in the Canadian Arctic, having already flooded a nearby patch (*darker blue*) to thicken it.

Arctic

A HAZE OF ICE CRYSTALS in the air created a halo around the low sun as three snowmobiles thundered onto the sea ice on a February morning in far northern Canada. Wisps of snow blew across the white expanse. It was –26 degrees Celsius as we left Cambridge Bay, an Inuit village in a vast archipelago of treeless islands and ice-choked channels. This temperature was relatively warm—six degrees C above average. The winter had been the mildest in 75 years. The sea ice covering the Arctic Ocean was at its smallest extent on record. Scientists predict that within the next 15 years this ice cap will disappear in summer for the first time in millennia, accelerating global warming. The U.K. company Real Ice, whose heavily bundled team was bouncing around on the other two snowmobiles ahead of mine, hopes to prevent that outcome with an effort that has been called extremely ambitious, insane or even dangerous.

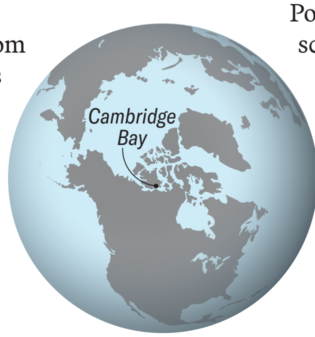
Alec Luhn wrote the feature "Out of Thin Air" about carbon capture in our September 2024 issue. He is an award-winning climate journalist who has reported from a town invaded by polar bears, the only floating nuclear power plant and the coldest inhabited place on Earth.

This story was produced in partnership with the Pulitzer Center's Ocean Reporting Network.

At a spot seven kilometers from the village, Real Ice co-founder Cían Sherwin, an Irishman with a red beanie and scraggy goatee, hopped off his snowmobile and started drilling with a long electric auger. A gob of water and frozen shavings sloshed up and out of the hole as he punctured the underside of the ice more than a meter below. Inuit guide David Kavanna widened the opening with a spearlike ice saw, then placed a wood box around it. Sherwin lowered an aluminum pump, which looked like a large coffee urn attached to a curved rubber hose, through the hole. He plugged a cable into a battery pack. After a few seconds water began pouring out of the hose, spilling onto the ice in an ethereal shade of blue. As it congeals, "the water acts almost like lava," Sherwin said. "The ice formation starts almost instantly."

Thin, broad sheets of ice expand from the ice cap's edges in winter, when it's dark and cold, and melt away in summer, when the sun shines 24 hours a day. The ice acts like a giant mirror, reflecting up to 90 percent of the sun's radiation back toward space. Ocean water, in contrast, absorbs 90 percent of sunlight. The ice cap's core of so-called multiyear ice, which persists year-round, has shrunk by about 40 percent in four decades, kicking off a vicious cycle: as more ice melts, more ocean water is exposed, and that water warms further, melting even more ice. If the ice starts disappearing entirely in summer, global temperatures could rise an extra 0.19 degree C by 2050.

Real Ice is trying to thicken seasonal ice so it lasts longer into the warm months, keeping the planet cool. Sherwin hopes pumping could someday refreeze a million square kilometers of both seasonal and multiyear ice—an area the size of Texas and New Mexico combined and about a fifth of what's now left in summer—to stop the ice cap's death spiral. All it would take, Real Ice says, is half a million ice-making robots.



Polar geoengineering on such an enormous scale could help slow warming until the world finally weans itself off coal, oil and natural gas. Many scientists think it will never work. The researchers at Real Ice argue we no longer have any option but to try; studies suggest that even slashing fossil-fuel use may not save summertime sea ice. "It's sad that

Map by Dolly Holmes

Real Ice co-founder Cían Sherwin drills through the ice sheet, a meter thick, into seawater below (*left*). Inuit hunter David Kavanna guides the team to prospective sites seven kilometers away from Cambridge Bay (*right*).

it's ended up that way, but we've got to do something about it," Sherwin said to me out on the frozen plain. "Emissions reduction is just not enough anymore."

CAMBRIDGE BAY, which British explorers named for a 19th-century Duke of Cambridge, is a town of 1,800 mostly Inuit inhabitants located across from the Canadian mainland on Victoria Island, one of the world's largest islands. When I landed at the one-room airport on a twin-engine turboprop, I was greeted by a stuffed musk ox and a placard about the 1845 British naval expedition of John Franklin. Cambridge Bay lies along the Northwest Passage, an icy sea route between Europe and Asia sought by explorers for 400 years. Franklin's two ships, *Erebus* and *Terror,* were trapped in the polar sea ice that surges down toward Cambridge Bay in winter, buckling into ridges up to 10 meters high. All 129 men onboard died of cold, starvation or disease. These days cruise ships coast through the passage every year, often visiting grave sites of Franklin expedition members.

The Inuit call Cambridge Bay *Ikaluktutiak,* meaning "good fishing place." For millennia their nomadic ancestors came here to fish Arctic char, a silvery-orange cousin of the brook trout. Inuit started living here full-time in the 1940s and 1950s, when the U.S. military hired them to help build a navigation tower and a radar station to detect Soviet bombers coming over the pole. The cold war also led to the idea of controlling the Arctic environment. The U.S.S.R. discussed destroying sea ice with coal dust or explosions and detonated three nuclear devices to try to excavate an Arctic canal. In the U.S., physicist Edward Teller's Project Plowshare nearly got approval to gouge out a harbor in Alaska with atomic bombs.

Geoengineering today is intended to cool Earth to fend off climate change. Some scientists and entrepreneurs are focused on dispersing sulfate particles in the stratosphere to block sunlight, which could lessen heating but also disrupt global weather patterns such as the South Asian monsoon. Mexico recently announced a ban on this solar geoengineering after Silicon Valley start-up Make Sunsets launched two balloons full of sulfur dioxide there. The city of Alameda, Calif., halted an experiment to spray sea-salt particles skyward to make clouds more reflective. Field trials targeting the Arctic, the Antarctic and the "third pole" of colossal glaciers in the Himalayas have stirred up less controversy, perhaps because unintended consequences would be confined largely to those distant places. In Iceland and India, Silicon Valley nonprofit Bright Ice Initiative has scattered tiny glass beads on glaciers to try to reflect more sunlight and slow the melting. Chinese agencies have blown chemical smoke into clouds with rockets, planes, drones and chimneys to provoke snowfall over glaciers on the Tibetan plateau. Researchers in Scandinavia are developing giant curtains that could be anchored to the seabed to block warm ocean

water from melting the undersides of ice shelves in Antarctica. Billions of dollars would be needed to affect the climate.

Biologist Brendan Kelly ties a water pump to a wood box erected around a hole in the ice (*left*). A pump, powered by batteries, pours seawater from under the ice onto the surface, where it floods snow and makes new ice, thickening the sheet so it will last longer in the coming summer's sun (*right*).

The idea for thickening ice came from outer space. At a 2012 conference a fractious forum about global warming soured Arizona State University astrophysicist Steve Desch's hopes for quick climate action. Desch, who studies icy bodies such as Pluto's moon Charon, wondered whether we could buy time by making ice in the Arctic. The problem is that sea ice freezes from below. Once the first layer forms, it insulates the seawater from the air, which can be 50 degrees C colder. The thicker the ice gets, the slower it grows. In 2016 Desch published a paper proposing that wind-powered pumps could thicken sea ice by pulling up water from below and spraying it across the top.

Around that time, students at Bangor University in Wales were inspired by a documentary on the Arctic to construct a "re-icing machine," an ungainly spindle of hoses that twirled like a lawn sprinkler. One of those students was Sherwin. Encouraged by Desch's paper, he and London entrepreneur Simon Woods founded Real Ice in 2022 to see whether sea-ice thickening could scale up. They eventually recruited Desch and several sea-ice scientists as advisers. The company put its first water onto ice in Nome, Alaska, in January 2023, ditching the sprinkler for a commercial pump. They moved to the Canadian High Arctic Research Station in Cambridge Bay the next year to do more. "It's not exactly the same as a natural process, but it's as close as you can get," Desch says.

AFTER THE TEAM DRILLED the first hole that February morning and started the pump, we snowmobiled to a destination pinpointed by GPS several hundred meters away. Again the group drilled and inserted a pump, and water began whooshing out. In all, we installed four pumps in four places. As water pooled, the edges crept outward, soaking into the pockmarked snow, which was up to 25 centimeters (10 inches) thick and crusty like hardened white frosting. Within hours the pool would coagulate into electric-blue slush, like a gas station Slurpee.

After a lunch of fruit bars and potato chips around a tiny gas heater in the team's rescue tent, we went to a site the crew had pumped a day earlier. Under a dusting of snow lay flat gray ice. With a drill bit almost as tall as himself, one of the volunteers bored a hole and dropped in a measuring tape with fold-out brass arms at its end. The ice was 152 centimeters thick; almost 30 centimeters of ice had been added, compared with untouched sites they measured.

The ice would thicken further in coming weeks. Because snow is a better insulator than ice—this quality is why igloos work so well—flooding and freezing the snow could allow more cold to penetrate to the ice's underside, creating more ice. After Real Ice thickened 4,100 square meters of ice here in winter 2023–2024, the crew came back in May 2024 to find a significant increase. Across the area they had pumped, ice thickness was 1.9 meters, compared with 1.44 meters in other places. "Ice growth from below—that's the really efficient part," Woods told me as he drilled a measuring hole at another refrozen site.

But snow is also a better mirror than ice, which could complicate the picture. Sea ice covered by snow reflects 90 percent of solar radiation, whereas bare sea ice reflects 50 to 70 percent. Real Ice would need snow to accumulate in spring to replenish the snow it flooded in winter, or the process could increase melting.

That's just one way flooding snow could backfire. As seawater freezes, the salt in it is ejected from the ice crystals, leading ever saltier pockets of brine to form on the surface. Salt lowers the freezing point of ice, whether on winter roads or the sea. If pumping seawater leaves more salt on the surface in summertime, it could end up accelerating the disappearance of the ice.

So far this doesn't seem to be happening. On another morning Woods put a hollow red barrel on the drill and bored into the ice at a refrozen site to extract an ice core about as long and thick as his arm. He held it up to the pale sun, which illuminated hairline channels where the salty fluid had eaten its way through the ice. "This natural process helps the brine to migrate back into the ocean," he said.

It's still not clear how ice thickening will affect sea life, starting with the microscopic algae that grow on the underside of the ice. They're eaten by zooplankton, which are eaten by fish, which are eaten by mammals. On a different morning I snowmobiled with University of Alaska Fairbanks marine biologist Brendan Kelly to a low ridge formed by two enormous plates of ice pushing together. A polar science adviser in President Barack Obama's administration, Kelly has studied seals and polar bears for more than four decades. In that time he's also watched fossil-fuel emissions march steadily upward. So despite his discomfort with geoengineering, he agreed to advise Real Ice.

In the hazy light, the monochrome landscape seemed devoid of life. But as we crunched on foot along the snow caking the ridge, Kelly stopped to point out an Arctic fox footprint. Farther on he found a urine stain, then desiccated green scat, then a small pit. "Seal, probably," Kelly said. In spring, ringed seals claw holes through snowdrifts. They hide their fuzzy white pups in these lairs while they dive for fish and crustaceans. Foxes and polar bears dig around to try to find the pups. Kelly scooped at the firm snow, tiny icicles swaying from his white mustache, but couldn't find a lair.

Polar bears also depend on snow. They excavate dens in larger drifts to warm their cubs, which are born the size of a guinea pig. Most Arctic snow tends to fall in late autumn. It's unknown whether enough new snow would build up after wintertime ice thickening for bears and seals to make dens in spring. Of course, polar bears and seals are already expected to decline as their sea-ice habitat melts away. Is Real Ice doing more harm than good by pumping seawater into this environment, melting the snow? "We don't know that," Kelly said. "But we need to know it."

ACROSS TWO MONTHS last winter, Real Ice pumped water through almost 200 holes. Drills and snowmobiles broke, team members got frostnip, and Arctic foxes chewed through long, thin thermistor cables used to measure temperature in the snow and ice. The researchers thickened 250,000 square meters of sea ice. The ice cap is losing 300,000 times that area every year.

The key to scaling up is to "bring the engineering underwater," Sherwin told me later. The Sant'Anna School of Advanced Studies in Pisa, Italy, is developing an underwater drone two meters long that will bore through ice from below with a heated pipe and start pumping water up through it. In renderings, it looks like a folding pocketknife with a pipe instead of a blade. Real Ice hopes to test a prototype this year, says co-CEO Andrea Ceccolini, an Italian computer scientist and investor who joined the company in 2022.

The plan is to thicken 100 square kilometers of sea ice in winter 2027–2028 to demonstrate the technique to governments and investors. The approach verges on the fantastic. A swarm of 50 drones would melt holes in minutes and pump water as their infrared cameras monitored the progress. Technicians on a floating or onshore hub would swap out the drones' batteries, plugging the old ones into chargers powered by wind turbines or by green hydrogen or ammonia brought in by ship. Tapping into electricity from Canada's Nunavut region would contribute to climate change because most of it is generated from diesel fuel.

The ultimate goal of thickening one million square kilometers of sea ice would take an estimated 500,000 drones, which would consume two terawatt-hours of electricity and require 20,000 people to service them, according to rough math Ceccolini has done. The cost would be $10 billion annually. The drones would vastly exceed the 3,800 Argo robot sensors circulating in oceans worldwide, and drone experts say a revolution in battery technology would be needed.

How much global warming could be countered through sea-ice preservation depends on numerous variables affecting sunlight and melt dynamics. Preserving a million square kilometers of sea ice for one additional summer month would cool Earth as much as removing 930 million metric tons of carbon dioxide from the atmosphere over 20 years, Real Ice estimates. For these results, $10 billion is actually cheap, Ceccolini says, and the cooling would be immediate. Capturing that much CO_2 from the air with existing machines would currently cost at least $465 billion. For perspective, humanity emits 910 million tons of CO_2 every eight days, with no end in sight. Thickening sea ice is a Band-Aid "while you cure the patient—the planet—properly," Ceccolini says.

Every day in Cambridge Bay, after three or four hours of flooding, the team used an ice ax to hack each pump out of its hole. Fat white frost flowers formed on top of the solidifying surface. The speed of the freeze was striking—but so was the immensity of the frozen plain stretching to the horizon. It was hard to envision hundreds of thousands of drones popping through the ice day after day, all winter long, for decades.

THE ONLY HIGHWAY in Cambridge Bay is the sea ice. In winter and spring, Inuit residents snowmobile hundreds of kilometers over it to go ice fishing and hunt musk ox and seals, local hunter Brandon Langan told me in his living room, a black musk ox hide hanging behind him. He works part-time for Real Ice flying airborne drones to monitor the thickened ice's reflectivity. When the ice recedes in summer, the Inuit fish the Arctic char that run into the bay from lakes and streams. When ice returns in fall, they hunt the caribou that cross it to the mainland. Two out of every three meals are fish or game. "Sea ice, to us, it's life," Langan said. "It helps us get our food. It gives us our clothing."

Now hunters who used to start moving on the ice in October have to delay until December. A few have even fallen through. In spring, the ice cracks and melts sooner. Ice loss has diminished the local caribou herd by 90 percent; the animals go hungry waiting to cross, and when bottled up for too long on the shore, they're easier prey for wolves. Hundreds of caribou have drowned after breaking through the ice. One hunter who had previously been a guide for Real Ice told me at the cultural center in the high school library that he hopes ice thickening could rejuvenate game populations.

Inuit insights are vital. Throughout history scientists and explorers often ignored Indigenous knowledge of the Arctic. The last time anyone saw the Franklin expedition was when Inuit hunters encountered starving sailors dragging a lifeboat across the ice in Washington Bay, clad in wool rather than furs. Franklin was dead, and the remaining explorers traded the Inuit beads for seal meat—they apparently didn't know how to hunt seal themselves. Later, native people found mutilated bodies farther south, indicating the explorers had resorted to cannibalism. Charles Dickens dismissed these reports, which were later confirmed, as "the wild tales of a herd of savages" and suggested the Inuit had slain Franklin's men. This colonial mindset would persist as the Arctic came under government control. Canada and Alaska took Indigenous children, including some from Cambridge Bay, away to be reeducated in abusive residential schools, where thousands died.

A week after I met with Langan I talked with Inuit Circumpolar Council international chairwoman Sara Olsvig, who has spoken out against testing the seabed-curtain idea in her native Greenland. She says governments need to start regulating geoengineering, and researchers need to seek the free, prior and informed consent of local communities. When somebody claims, "'We need your piece of land in the name of a greater good,' that's exactly what happened when we were colonized," Olsvig says.

Real Ice obtained permits from Nunavut's Inuit government, as well as the Cambridge Bay hunters-and-trappers organization. Ceccolini says the operation will shut down if ice thickening proves ineffective or damaging. Although the company may patent its drone technology, its articles of association prohibit it from distributing profits. But it would consider founding a new company with Indigenous part-ownership if it decided to scale up, Ceccolini says.

Local elders are hesitant. They gather at the cultural center on weekdays to sew fur boots and mittens and speak the local language. During a break for black tea and candied Arctic char, I asked three of them about the sea-ice thickening. They would be concerned about the drones if Real Ice conducted its 100-square-kilometer demonstration, a key step to scaling up, in the strait near Cambridge Bay rather than farther north. "If they start doing that under the water, we're going to get no more fish, no more seal, no more nothing," said Annie Atighioyak, who was born in an igloo on the sea ice in 1940.

AS GLOBAL FOSSIL-FUEL emissions keep rising, attitudes about geoengineering are starting to change. Two weeks before I arrived in Cambridge Bay I went to an annual Arctic science conference at the Oceanographic Institute of Monaco. Frederik Paulsen, a Swedish pharmaceutical billionaire in a tailored suit and rimless glasses, took the podium. Though not a scientist, Paulsen was the first person to reach all eight poles—the geographic, geomagnetic, magnetic and least accessible poles of each hemisphere—and was onboard one of the two submersibles that planted a Russian flag on the North Pole seabed in 2007.

In 2023, while flying over Greenland in an ultralight aircraft, Paulsen was startled to notice that the once brilliant ice sheet was turning darker as less fresh snow fell. He said he decided only "more drastic solutions" could avoid catastrophic climate impacts, given our failure to rein in fossil fuels. It's

Sherwin inspects a core drilled from a location where pumps had operated earlier.

not enough to just study climate, he scolded the scientists. "Now is the time to act."

The University of the Arctic, a network of educational institutions that Paulsen chairs, has rated the feasibility of 61 polar interventions, from spraying glaciers with ski-resort snow guns to cables that stop icebergs from drifting south. At the conference, John Moore, a University of Lapland glaciologist, presented the seabed-curtain idea. Also there was Fonger Ypma of Arctic Reflections, a Dutch sea-ice-thickening company that has done field trials in Newfoundland and Svalbard. Last year he went to Cambridge Bay to learn from Real Ice, but he hopes to deploy large movable pumping platforms rather than drones.

The surge of interest has created a schism in polar science. In October 2024 a preprint paper by 42 top glaciologists condemned ice thickening and other polar geoengineering techniques as dangerous and unfeasible. Seabed curtains could disrupt nutrient flows to CO_2-consuming phytoplankton. Spreading tiny glass spheres across mountain glaciers could decrease the reflectivity of ice covered in fresh snow. But the overarching concern is that geoengineering fixes are "making decarbonization a lot less attractive," according to Heidi Sevestre, one of the paper's authors, who visited an Arctic Reflections trial last year. What they are offering "doesn't attack the cause of the issue, the fossil fuels," she says.

At the Monaco conference, Kim Holmén, a Norwegian Polar Institute climate scientist who has spent more than three decades on Svalbard, the fastest-warming place on Earth, argued that trying to undo the harms of our technology with even more technology was folly. "I make mistakes every day, you make mistakes every day, and if we create a system where it must work every day, it will fail," he said. Critics say it would be more effective to put geoengineering funds toward cutting emissions.

The amount being spent on Arctic geoengineering is small but growing. Arctic Reflections has raised $1.1 million and Moore $2 million. Real Ice's directors have committed $5 million to its ice-thickening project, only a fraction of the cost for a 100-square-kilometer demonstration. It's hard to imagine state agencies allocating $10 billion a year for sea-ice thickening, especially with China, Russia and reportedly the U.S. looking to develop Arctic shipping routes; for them, less ice is better. Brazil's Amazon Fund for rainforest conservation, which Real Ice has held up as a possible funding model, has collected only $780 million from governments.

Private investors might mean fewer political obstacles. In March, Paulsen, who's offering a €100,000 prize for projects "reversing Arctic change," convened a dinner in Geneva to introduce geoengineering researchers—including a Real Ice adviser—to two dozen potential donors. He wants to hold similar "adopt-a-billionaire" gatherings in the U.S. He also claims he's discussed geoengineering with officials from the Trump administration, which withdrew the U.S. from the Paris climate agreement. The administration didn't respond to a request for comment.

Real Ice and Arctic Reflections would like to eventually sell "cooling credits," a strategy used by Make Sunsets. Individuals and companies that want to compensate for their CO_2 emissions pay that start-up to launch balloons full of sunlight-blocking sulfur dioxide. Carbon credits have paid for the planting of trees to remove tens of millions of tons of CO_2 from the atmosphere. But the credit arrangements also have been criticized as a "license to pollute" to avoid fossil-fuel reductions. Some of the biggest buyers are tech firms such as Microsoft, whose emissions are swelling as the company builds AI data centers.

Kelly, the former White House adviser, is indeed worried that geoengineering could be "hijacked" by oil or tech companies as an excuse to continue business as usual. But he's more concerned about the gigantic geoengineering experiment he says we're already conducting by emitting tens of billions of tons of greenhouse gases every year. Ice companies just have to be willing to shut down their technology if it starts harming nature or undermining climate goals, he told me as we drank coffee at the research station in Cambridge Bay. They have to be willing to turn back, unlike Franklin and other overconfident explorers who came here to discover the Northwest Passage. "We all have to keep asking ourselves and checking ourselves and one another: Have we slid into hubris?" Kelly said. "The alternative is to think [we humans] know what's best, that we can get through the passage." ●

FROM OUR ARCHIVES
Sir John Franklin's Expedition. The Editors; June 2, 1849. ScientificAmerican.com/archive

Frost flowers form when very cold, still air rests on newly formed ice (*at left*), which is relatively much warmer. Vapor rising from the ice rapidly crystalizes, creating the flowers.

BIOLOGY

The Social Lives of Mitochondria

When these energy-giving organelles thrive, so do we

BY MARTIN PICARD | ILLUSTRATIONS BY JENNIFER N. R. SMITH

I ALWAYS WANTED TO UNDERSTAND LIFE. What moves us? What allows us to heal and thrive? And what goes wrong when we get sick or when we eventually stop breathing and die? My search for answers to these stupendously ambitious questions led me, it now seems inexorably, to mitochondria.

In biology classes from high school through university, I learned that mitochondria are little objects that reside within each cell and serve as "powerhouses," combining oxygen and food to yield energy for the body. This idea of mitochondria being little batteries with a built-in charger, about as interesting as the one in my phone, left me unprepared for the vital reality of these organelles when I first saw them under a microscope in 2011. They were luminous because of a glowing dye I had put in them, and they were dynamic—constantly moving, stretching, morphing, touching one another. They were beautiful. That night, a graduate student alone in a dark laboratory in Newcastle upon Tyne in England, I became a mitochondriac: hooked on mitochondria.

A profound insight by biologist Lynn Margulis helped me make some sense of what I was seeing. She postulated in 1967 that mitochondria descend from a bacterium that was engulfed by a larger ancestral cell about 1.5 billion years ago. Instead of consuming this tidbit, the larger cell let it continue living within. Margulis called this event endosymbiosis, which means, roughly, "living or working together from the inside." The host cell had no energy source that used oxygen—which, thanks to plants, was already abundant in the atmosphere; mitochondria filled this gap. The unlikely union allowed cells to communicate and cooperate and let their awareness expand beyond their own boundaries, enabling a more complex future in the form of multicellular animals. Mitochondria made cells social, binding them in a contract whereby the survival of each cell depends on every other one, and thus made us possible.

Amazingly, my co-workers and I have discovered that mitochondria are themselves social beings. At least, they foreshadow sociality. Like the bacterium they descended from, they have a life cycle: old ones die out, and new ones are born out of existing ones. Communities of these organelles live within each cell, usually clustered around the nucleus. Mitochondria communicate, both within their own cells and among other cells, reaching out to support one another in times of need and generally helping the community flourish. They produce the heat that keeps our bodies warm. They receive signals about aspects of the environment in which we live, such as air pollution levels and stress triggers, and then integrate this information and emit signals such as molecules that regulate processes within the cell and, indeed, throughout the body.

When our mitochondria thrive, so do we. When they malfunction—when, for instance, their ability to change energy into forms required for biochemical reactions is impaired—we may experience conditions as diverse as diabetes, cancer, autism and neurodegenerative disorders. And as mitochondria accumulate defects over a lifetime of stress and other insults, they contribute to aging and, ultimately, death. To understand these processes—to see how to sustain physical and mental health—it helps to understand how energy moves through our bodies and minds. That requires a deeper look into mitochondria and their social lives.

LONG BEFORE I GOT MY FIRST glimpse of mitochondria, I had boned up on the basics of their structure and biology. We inherit our mitochondria from our mother—from the egg cell, to be precise. Mitochondria have their own DNA, which consists of only 37 genes, compared with the thousands of genes in the spiraling chromosomes inside the cell nucleus. This ring of mi-

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tochondrial DNA, or mtDNA, is sheltered within two membranes. The outer shell, shaped like the skin of a sausage, encases the mitochondrion and selectively allows molecules to enter or exit. The inner membrane is made of densely packed proteins and has many folds, called cristae, which serve as a site for chemical reactions, much like the plates suspended inside a battery.

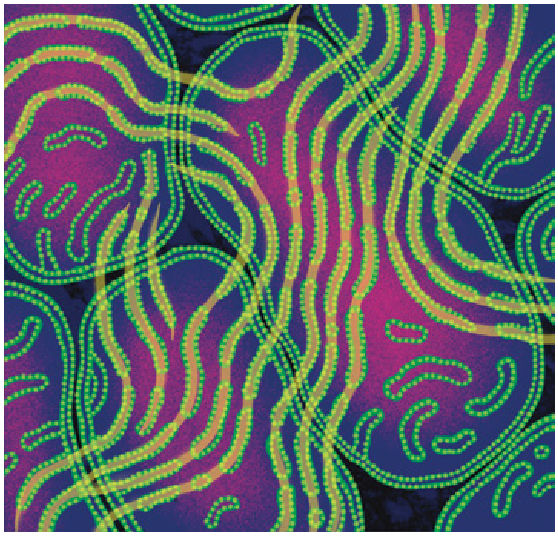
In the 1960s British biochemists Peter Mitchell and Jennifer Moyle discovered how electrons derived from carbon in food combine with oxygen in the cristae, releasing a spark of energy that is captured as a gradient in electrical voltage across the membrane. This voltage provides the driving force for all processes in the body and brain, from warming to manufacturing molecules to thinking. Mitochondria also produce a molecule called adenosine triphosphate, which serves as a portable unit of energy that powers hundreds of biochemical reactions within each cell.

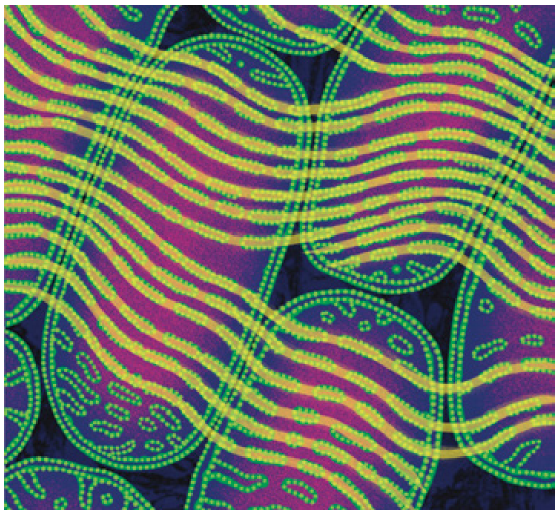
Returning from the U.K., I started a postdoctoral fellowship with geneticist and evolutionary biologist Douglas Wallace at the Center for Mitochondrial and Epigenomic Medicine at Children's Hospital of Philadelphia. In 1988 Wallace had discovered the first-ever link between a mutation in mtDNA and a human disease. He had gone on to map some of mitochondrial biology's fundamental connections to various diseases and the aging process, laying the foundation of the field of mitochondrial medicine. In Philadelphia, I began working with a fellow postdoc, Meagan McManus, who wanted to understand how defective mitochondria could cause cardiovascular and neurological diseases. McManus asked me to photograph with an electron microscope the mitochondria in the hearts of mice with a specific mtDNA mutation that led to heart failure.

Our team was also experimenting with three-dimensional imaging using electron tomography, the same technology that allows a radiologist to see a patient's internal organs in 3D. Weeks later, the director of this project, Dewight Williams of the University of Pennsylvania, brought me to a room where the million-dollar tomography microscope stood, as high as the ceiling, to show me reconstructed movies of mitochondria.

The tomography gave us a 3D view of the cristae. Some mitochondria in the hearts of the sick mice had jagged, highly irregular cristae—the unhealthy look I had been seeing in the 2D pictures. But one thing showed up in 3D that we had never seen in the flat images: even when mitochondria looked unhealthy, their cristae looked healthy at places where the mitochondria touched one another. They were interacting, helping one another's internal organization. These mito-mito junctions also had more cristae than any other part of the same mitochondrion. "Meagan has to see this!" I thought, rushing to the lab across campus.

As I restarted the movie for McManus, I narrated what I had seen a few minutes earlier: "Mitochondria are influencing one another!" We watched the looping video a few times. Then McManus said, her voice pitched high with excitement, "And the cristae line up! The cristae line up between mitochondria!" She drew a line with her extended finger across a junction between mitochondria.

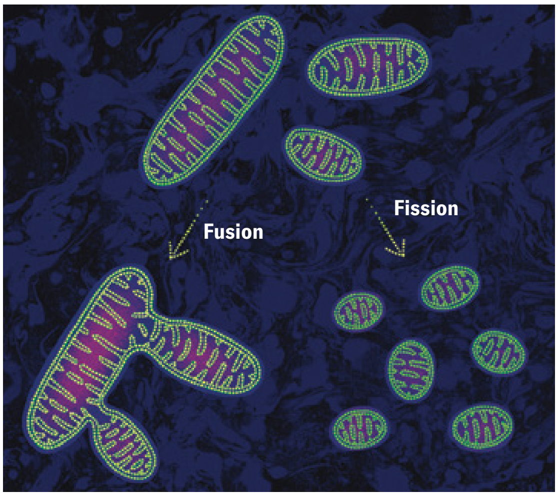




I had pored over thousands of electron microscopy images from the best microscopists. Never had I heard about cristae in one mitochondrion aligning with the cristae of another mitochondrion. While in Newcastle, I had seen a 1983 paper by Russian scientists Lora E. Bakeeva and Vladimir P. Skulachev describing "intermitochondrial contacts," and I had demonstrated that these contacts increased after exercise—perhaps increasing energy efficiency. How had we all missed the alignment? Yet instead of lying there as parallel plates, like textbooks often portrayed them, the cristae formed parallel ribbons undulating across mitochondria. It almost looked like the cristae were helping their neighbors organize to achieve the typical, healthy, regular array.

At the next lab meeting, I suggested that these patterns looked like iron filings aligned around a magnet. Cristae are full of iron-sulfur clusters that may be paramagnetic. If they are, maybe there were electromagnetic fields induced by the flow of electrical charge across the cristae? Could they induce the cristae to line up? So far this hypothesis appears to be the best one for how cristae align across mitochondria. For me, it also opened the door to thinking about how the forces of physics might have contributed to the evolution of multicellular life—all the way to us.

THIS DISCOVERY and the thoughts it spurred changed my view of mitochondria forever. Hundreds of hours in the dark dungeon where I studied mitochondria and numerous collaborations later, I had learned one important lesson: mitochondria exchange information. The fingerprint of that exchange lay right there in the patterns of their cristae. Further studies at the University of Tsukuba in Japan and elsewhere, using cells with varying levels of mitochondrial dysfunction caused by mtDNA mutations, showed that healthy mitochondria can donate intact mtDNA to mutant mitochondria. In conditions of scarce energy supply, mitochondria fuse with one another into long strands to share mtDNA. Isolated mitochondria without mtDNA or with mutated mtDNA can similarly fuse with healthy mitochondria, restoring their normal function.

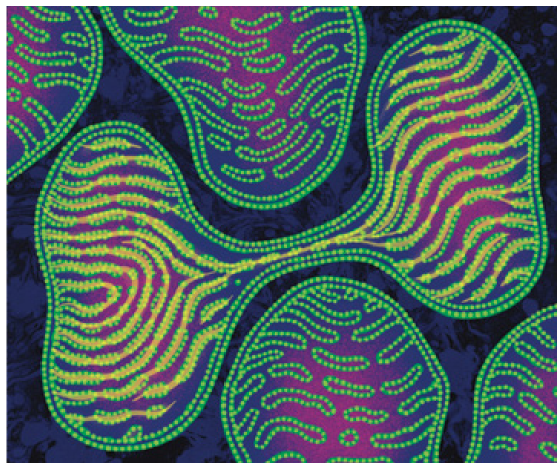


Fusion enhances the resilience not only of mitochondria but also of cells; interfering with these interactions leads to isolated mitochondria that accumulate mtDNA defects and ultimately die, along with the cells they live in. In people, decreased levels of mitofusin 2, a protein located in the outer mitochondrial membrane that helps with fusion, are correlated with neurodegeneration. And mice with mitochondria that have been engineered to impede fusion in the nucleus accumbens, a brain region involved in regulating reward, are more anxious.

Could there be yet other ways in which mitochondria communicate? Could they act like their bacterial ancestors, which build biofilms and use membrane protrusions, electrical fields and secreted molecules to cooperate and conquer the living world with their versatile collective behaviors? Could mitochondrial communication reveal a broader internal universe of energy and information exchange? Could mitochondrial junctions and aligned cristae operate like neuronal synapses, with the resulting mitochondrial collective behaving essentially like an intracellular brain?

IN 2016, SHORTLY AFTER STARTING my own lab at Columbia University, I was back in Newcastle on a visit to Doug Turnbull's Wellcome Center for Mitochondrial Research. I was again sitting at the electron microscope, this time with a stellar British graduate student, Amy Vincent. We were imaging muscle from the calf of a woman with an mtDNA mutation that caused a rare mitochondrial disease. By coincidence, her mutation was similar to the one McManus's mice had had.

What Vincent and I found that afternoon opened another avenue of inquiry. In front of our eyes lay mitochondrial nanotunnels: thin membrane protrusions—the same kind that bacteria use to share their circular DNA! For the first time in humans, Vincent and I saw that mitochondria send thin tubular structures out toward one another, like feelers that some solitary cells use to search for a more hospitable environment or a healthy fellow cell. By imaging dozens of other muscle samples, we found that people whose mitochondria don't work well have more nanotunnels. It was as if unhealthy mitochondria with mtDNA mutations were reaching out for help.



Perhaps the most remarkable aspect of the mitochondrial collective, however, is that mitochondria from different parts of the body talk to one another, using hormones as their language. Mitochondria produce the steroid hormones we use for sustaining and reproducing life. Cortisol, the hormone that increases blood glucose levels to fuel the stress response, is made in the mitochondria of the adrenal glands, which sit on top of the kidneys. Testosterone, estrogen and progesterone are synthesized mainly by mitochondria in the reproductive organs. Interestingly, brain mitochondria have receptors to sense both stress and sex hormones. So we have a population of mitochondria in the adrenal glands that signal directly, via the blood, to mitochondria in the brain.

Further, mitochondria are not all created equal. In the same way that humans develop specialties in different social and economic roles and organs specialize in executing complementary functions (the liver feeds other organs, the heart pumps, the brain integrates information and issues directives), mitochondria also specialize. Across organs and cell types, mitochondria look different. Their protein contents are different. They move differently. And their ability to sense, integrate and signal specific information varies according to the cell they inhabit. Mitochondrial specialization most likely affords gains in efficiency, allowing an organism to survive at a lower overall energy cost.

My co-workers and I recently built the first map of mitochondria in the human brain. Even within this single organ there are different types of mitochondria in different parts of the cortex and in deeper, subcortical brain regions. The brain uses 20 percent of the body's energy, despite constituting only 2 percent of the body's mass, so an efficient source of power is critical to its functioning. My colleagues, notably, Michel Thiebaut de Schotten of the French National Center for Scientific Research and Eugene V. Mosharov of Columbia, and I found that the more recently evolved brain areas, which have the highest energy expenditure, have mitochondria that are more strongly specialized for energy transformation.

Mitochondria within a cell may also look very different from one another. For example, in neurons, "dendritic" mitochondria are found in the fibers, or dendrites, through which neurons receive signals from other cells. These mitochondria are stable filaments that stretch over 10 to 30 microns—a stupendously long distance for this type of structure—and have several mtDNA copies. "Axonal" mitochondria move along the linear axons, which conduct signals to other neurons, as if they were cellular highways. They are generally short and stubby (up to a micron in length), and many lack mtDNA. "Cytoplasmic" mitochondria cluster around the nucleus and look like something between the dendritic and axonal types. Similar grouping and specialization of mitochondria exists in muscle and fat cells.

These findings, taken together, led behavioral neuroscientist Carmen Sandi of the Swiss Federal Institute of Technology and me to propose in 2021 that mitochondria are social organelles. If you are like me and your eyebrow rises when you hear the term "social" applied to a subcellular organelle, you are having a normal reflex. Nevertheless, Sandi and I argue that mitochondria show all the features of social beings—a shared environment inside the cell or body, communication, formation of groups or types, synchronization of behavior, interdependence, and specialization in the tasks they perform.

In a subsequent paper, which required a painfully long review of more than 400 studies, Orian S. Shirihai of the University of California, Los Angeles, and I established that the mitochondrial collective operates as a mitochondrial information-processing system, or MIPS. Like the animals they exist within and support, which must respond flexibly to the environment, the mitochondria sense signals, integrate this information in the membrane potential of their cristae, and produce signals that regulate the genes of the cell and shape cell behavior.

Your eyes transform light into electrical impulses that coalesce into an image in your visual field, and your ears transform air-pressure waves into electrical pulses that you eventually perceive as sounds. Likewise, mitochondria transform dozens of hormonal, metabolic, chemical, and other information streams into their electrical membrane potential. This "bioenergetic" state then leads to the production of secondary messenger molecules that are intelligible to the nucleus. So in the same way you read messages on your phone, which receives signals, transforms them and projects decipherable information onto its screen, the nucleus of your cells can "read" the environment through the MIPS that surrounds it.

Rather than having supplementary roles like those of battery chargers, mitochondria are more like the motherboard of the cell. Genes sit inert in the nucleus until energy and the right message come along to turn some of them on and some others off. Mitochondria provide these messages, speaking the language of the epigenome—the malleable layer of regulation that sits on top of the genome to regulate its expression.

My colleague Timothy Shutt of the University of Calgary likes to call mitochondria the "CEO of the cell": the chief executive organelle. This metaphor captures how mitochondria not only are involved in integrating information but also give orders. They dictate whether the cell divides, differentiates or dies. Indeed, mitochondria have a veto on cell life or death. If the MIPS deems it necessary, it triggers programmed cell death, or apoptosis—a form of self-sacrifice for the greater good of the organism.

So vital are mitochondria that in difficult times cells may donate entire mitochondria to other cells. "In cellular emergencies, newly arrived mitochondria might kick-start tissue repair, fire up the immune system or rescue distressed cells from death," journalist Gemma Conroy noted in a *Nature* news story last April. Inside tumors, cancer cells and immune cells appear to compete for mitochondria, using them as a kind of bioweapon. An international effort I participated in, led by Jonathan R. Brestoff of the Washington University School of Medicine in St. Louis, recently created an entirely new lexicon to guide the emerging field of mitochondria transfer and transplantation.

ALL WELL AND GOOD, you may think. What does all this mean for my health or how long I'm going to live?

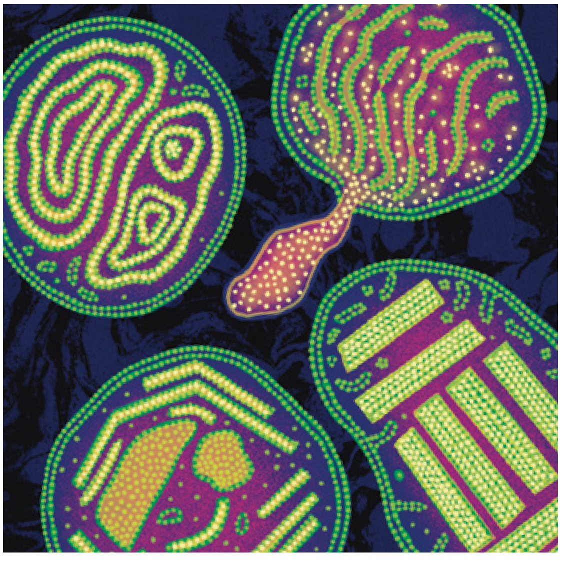
The short answer is that it may have everything to do with human health. Diabetes, neurodegenerative conditions, cancer and even mental health illnesses are all emerging as metabolic disorders involving malfunctioning mitochondria. And these findings are indicating new routes for intervention.

Mitochondria drive health—or disease—in several ways. One route derives from their role as energy processors. In an electrical circuit, if we crank up the input voltage too much, we can blow it out. Similarly, if our cells are exposed to too much glucose or fat—or, worse, both together, causing what doctors refer to as glucolipotoxicity—the mitochondria undergo fission and fragment into little bits, accumulate mtDNA defects, and produce signals that end up prematurely aging or killing the cell. Experiments in cells and in mice have shown that pharmacologically or genetically preventing mitochondrial fission induced by excessive glucose and fats may protect against insulin resistance.

Cancer, too, may be a disorder of cellular metabolism. Cancer cells can burn glucose without oxygen, which suggests either that something is wrong with their mitochondria or that they prefer to reserve mitochondria for use in cell division—and proliferation.

A second pathway is through mitochondria's influence on gene expression. Mitochondrial signals alter the expression of more than 66 percent of genes in the nuclear chromosomes. By changing which genes are expressed and to what extent, mutations in mtDNA may completely alter the nature, behavior and stress resilience of cells and ultimately of the whole organism.

Mitochondria can look terribly odd when sick. In people with mtDNA defects that cause rare mitochondrial diseases, such as the person in whose mitochondria we first saw nanotunnels, the cristae in particular can look somewhat alien—like crop circles with regular angles, paracrystalline inclusions, and other weird shapes.



Notably, abnormal mitochondrial shape and function are emerging as biomarkers and potential causes of cognitive and neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and others. Clinically, a neurobiological subtype of autism spectrum disorder involves defects in mitochondrial biology.

A third pathway is inflammation. When cells are injured or stressed, they may leak mtDNA into the cell's interior, the cytoplasm, or even into the blood. Along with Caroline Trumpff of Columbia, Anna Marsland and Brett Kaufman of the University of Pittsburgh, and other co-workers, I found that mental stress induced by having to speak in public for five minutes increased the amount of free-floating mtDNA in the blood. People in intensive care units who are grievously ill tend to have very high levels of mtDNA in their blood. Because mtDNA rings resemble bacterial DNA, immune cells see them as pathogens and mount an attack that can develop into inflammation. And inflammation, clinicians know well, is linked to the onset and progression of a host of chronic health conditions.

Just how defective mitochondria lead to illness in the body and mind is a question that has yet to be answered. But there are simple ways to ensure our mitochondria stay healthy. One is exercise. When you move vigorously, your cells consume energy rapidly, powering up the membrane potential of your mitochondria. If your exercise leaves you feeling out of breath, it is a sign that your mitochondria are working hard. Because the brain-body entity is expert at anticipating and preparing for the future, if you move in a way that activates your mitochondria, your body thinks, "Next time this happens, I'll be ready!" To get ready, it makes more mitochondria and keeps them working at their best.

Surprisingly, social connections, too, may promote the health of our brain mitochondria. In a major study led by David A. Bennett of Rush Medical College in Chicago, researchers asked hundreds of individuals aged 65 and older in the Chicago area to fill out surveys, take cognitive tests and give blood every year until they died. After death their brains were collected to enable analysis of their mitochondria. My colleague Trumpff used those data to ask whether positive mental states such as feeling purpose in life, optimism and a sense of connectedness—or, in contrast, negative mental states such as perceived stress, depression and social isolation—could be related to the mitochondria's ability to transform energy.

What Trumpff learned was remarkable: the amount of energy-transforming proteins in mitochondria in the prefrontal cortex was significantly correlated with how many positive and negative experiences people reported in the year before they died. This finding aligned with previous studies relating early-life adversity or daily mood markers such as feelings of love, closeness or trust to mitochondria in blood immune cells. Our states of mind might affect the biology of our mitochondria, modulating how well they transform energy.

Another intervention that can be remarkably effective is diet. Medical ketogenic therapy or "nutritional ketosis," which involves cutting out all refined sugars, limiting intake of carbohydrates, and making up the calorie difference with more proteins and fats, has been shown to sustainably reverse insulin resistance and type 2 diabetes. The ketogenic diet has been used for decades to ward off seizures and thereby "stabilize" the brain in children and adults with intractable and otherwise incurable epilepsy. A ketogenic diet can even ameliorate the mental state and cognitive function of people with Alzheimer's. It enhances brain-network stability, a marker of brain aging—and this function may explain why some people on the diet sleep better.

The ketogenic diet can have astonishing effects in other diseases as well, as evinced by the story of Lauren Kennedy West, a Canadian woman diagnosed with schizophrenia and bipolar disease at the age of 25. Her life progressively felt too difficult to navigate, "like there was no space for me in the world," she explained in a moving account of her journey posted on YouTube last year. In December 2023 West began nutritional ketogenic therapy. A couple of weeks later, she noticed she had more energy. Many of her symptoms lessened. After about nine months she was symptom-free, had tapered her medication in collaboration with her care team, and continued to feel better. Late in 2024 she took her last dose of antipsychotic medication.

West's experience parallels initial positive results from a pilot trial of 21 people with bipolar disease and schizophrenia. Numerous other clinical trials of the ketogenic diet for people with severe mental illnesses such as schizophrenia, depression, anxiety and obsessive compulsive disorder are currently in progress around the world. (Many of these trials are by funded by the Baszucki Group, a philanthropic foundation formed after Matt Baszucki, the son of the group's founders, successfully treated his bipolar disease with the ketogenic diet. In 2024 I received the Baszucki Prize in Science, which helps to fund my lab at Columbia.)

A new study of 28,995 people in the U.S., 4,484 of whom had significant depression symptoms, also supports the protective effects of low-sugar diets on mental health. People whose diet was "more ketogenic"—low in carbohydrates and sugars relative to lipids and proteins—were less than half as likely to develop depression compared with people whose diet was fairly rich in sugars.

How does it work? From a mitocentric perspective, the ketogenic diet does three things. First, it leads to the supply of an efficient fuel source by the liver, which feeds other organs in the body. If you fast or eat a ketogenic diet, your liver takes the fats from your love handles or your food and breaks them down into smaller bits called ketone bodies. This process happens inside the liver's mitochondria. Second, after entering the blood, ketone bodies reach the organs, some of which, including the brain, prefer ketone bodies over other fuels such as glucose, proteins and fats. So in the presence of various fuel sources, the brain will preferentially burn ketones.

The third thing may have to do with efficiency—and might explain why ketone bodies are the preferred fuel for the brain. Glucose has to traverse a number of hurdles before getting to neuron mitochondria—it detours through astrocytes, crosses several membranes and goes through several enzymatic reactions. In contrast, ketone bodies are taken up directly by the mitochondria in neurons, where they are burned. It's a far less convoluted path.

So ketosis, or the burning of ketone bodies, may exert its effects on the brain by enabling energy to directly flow between mitochondria. Ketones in your blood open a stream of communication between producer and consumer mitochondria, fostering their sociality throughout your body.

Rather than being like battery chargers, mitochondria are more like the motherboard of the cell.

ONCE WE REGARD MITOCHONDRIA as dynamic energy and information processors, an entirely new perspective of life emerges. Think of yourself as a waterfall. The waterfall exists only insofar as the water molecules keep flowing down. You learn as much about the waterfall when you scoop up a few inert H_2O molecules as you learn about how healthy a person is by sequencing their genome: close to nothing.

The waterfall cannot be understood from its parts, only from its movement. And once the flow stops, there is no more waterfall. The waterfall is not a thing that appears and disappears. It is a *process*—a process that flows and stops flowing. Like a waterfall, you are not a thing. You are a process—an energetic process, to be precise.

Your fundamentally energetic nature has two main implications. The first is that as a dynamic process, you are bound to change. Your body continually sheds, kills and makes cells. Your mind also changes. Some parts of your mind, such as your personality, are relatively stable. But then again, that can change, too—when you are "hangry," for instance, and become less than your best self. That's an energy deficit changing your mind.

Some drugs can dramatically change your mind. Psychedelics, for example, act on the serotonin system to desynchronize the human brain. They also dissolve the sense of self, or "ego." Change brain-energy patterns, change the mind. The mind, then, may essentially be an energy pattern. Further, energy flowing through your brain somehow *feels* like something. As Nirosha Murugan of Wilfrid Laurier University in Ontario and I recently postulated in a paper, humans may be wired to experience excessive resistance to energy flow as aversive. In contrast, smoothly flowing energy, as occurs after an enjoyable exercise session or when you are working on a stimulating project, feels good. When energy ceases flowing to your brain—if your heart stops, for example—your conscious awareness quickly fades, and you no longer are.

Does all this say anything useful about my original questions? I suspect we now have answers. The key to life and health may lie in how easily energy flows through your mitochondria with each breath you take. So next time you skip that appealing sugary treat, go outside for a stroll, hit the gym or decide to spend time with someone you care about, know that you are supporting your mitochondria. Keeping energy flowing through your mitochondrial collective may be the key to good health and a meaningful life. ●

FROM OUR ARCHIVES
A New Understanding of the Cell. Philip Ball; February 2025.
ScientificAmerican.com/archive

THE QUANTUM BUBBLE THAT COULD DESTROY THE UNIVERSE

A freak particle physics process could wipe out all galaxies and life—but it's wildly unlikely

BY MATTHEW VON HIPPEL
ILLUSTRATION BY MONDOLITHIC STUDIOS

MOST PEOPLE HAVE NEVER HEARD of vacuum decay, but if it happened it would be the biggest natural disaster in the universe. Sure, an asteroid could destroy a city or wipe out life on Earth. A supernova could fry the ozone layer. If a blast of energy from a spinning black hole hit our planet, it could rip apart the entire solar system. As dramatic as these disasters are, they'd still leave behind rocks, gas and dust. With time that matter could come together again, making new stars and planets and maybe life.

Vacuum decay is different. This cataclysm would result from a change in the Higgs field, a quantum field that pervades all of space. It would be triggered by pure chance, creating a bubble that would expand at almost the speed of light, transforming all in its path. Inside that bubble the laws of physics we take for granted would change, making matter as we know it (and, consequently, life) impossible.

According to physicists' current best estimates, vacuum decay is extremely unlikely, with an almost unthinkably small chance of its taking place close enough to our part of the universe to affect us. Still, the chance isn't zero, and some recent estimates suggest the likelihood might be slightly less minuscule than we used to think. Ultimately, though, the possibility of an apocalyptic quantum bubble shouldn't cause anyone to lose any sleep.

Even so, scientists have been studying how and why this scenario might play out. The answers to these questions don't just reveal some fascinating aspects of the quantum world—they may also turn the questions on their heads: rather than making us worry about the threat a vacuum bubble poses, the fact that the universe has survived this long without one may teach us something about the deepest unsolved problems in physics.

THE WORD "VACUUM" evokes the idea of empty space, and that's not too far from its meaning in the phrase "vacuum decay." For physicists, however, "empty" itself is relative.

All the objects we're used to—every animal, vegetable and mineral—are made up of atoms, and those atoms are made up of ripples in quantum fields. Each field is like a setting on a kind of universal control panel. If you could jiggle the electron switch on the

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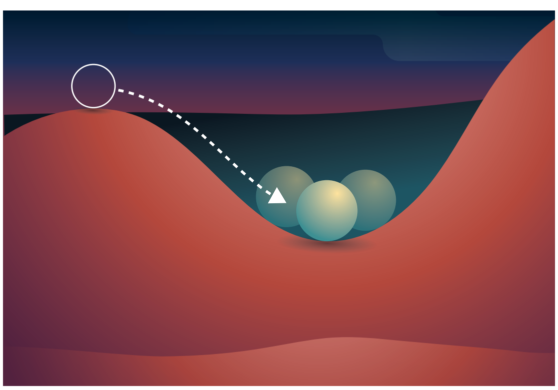
control panel, you'd see an electron pop into existence. Most of these switches have a default value of zero: electrons aren't likely to be in most places, for example. These defaults are sticky—it takes effort, in the form of energy, to push a switch out of its default position. How much energy it requires is determined by Albert Einstein's famous equation $E = mc^2$, which defines the relation between energy and mass: the more massive a particle, the stickier the default for the switch of its field.

You might think that in truly empty space, all these switches are set to zero. That's true for most quantum fields, but some have a different default. One such case is a quantum field proposed by several physicists in 1964, including British physicist Peter Higgs, for whom it was later named. Try to set the Higgs field to zero, and it will resist. The universe "wants" to have a certain amount of Higgsness in it, a default called a vacuum expectation value. It is this amount of Higgs field, instead of zero, that one finds in the vacuum of empty space.

Pushing the Higgs field from this default setting is quite difficult. Scientists finally accomplished it in 2012, when an experiment at the Large Hadron Collider (LHC) near Geneva managed to measure the tiniest, briefest possible shift in the Higgs field. Just as jiggling the electron switch makes an electron, jiggling the Higgs switch makes a particle called a Higgs boson. These particles swiftly vanish after we create them, with the Higgs switch rushing back to its default while knocking other, easier-to-shift switches around, creating particles such as electrons or photons instead. But LHC scientists managed to create enough Higgs bosons to definitively detect them and prove the Higgs field exists.

The Higgs field is special because it controls the mass of all other particles. In effect, it serves as a kind of master switch, determining how sticky all the other switches' defaults are. If you could grab the Higgs switch and drag it toward zero, you'd find that all the other switches became much easier to flick. In other words, a lower Higgs value would mean it took less energy to make an electron or a quark.

Physicists think of the task of moving the Higgs field from its default value as being a bit like rolling a boulder up a hill. If the boulder rests at the bottom of a valley, you can try to push it upward, but if you let it go, it will just roll down again.

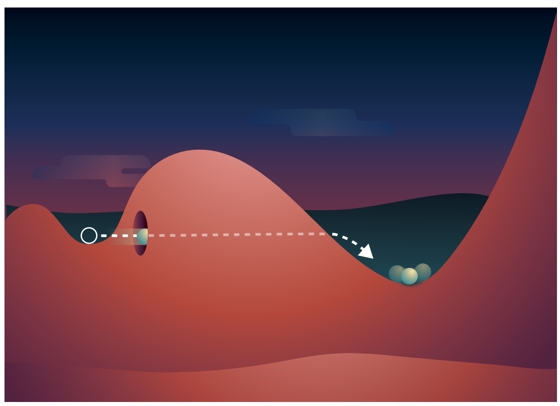


Inside the bubble the laws of physics we take for granted would change.

FOR THE HIGGS THEORY TO WORK, the Higgs field needs to have a setting that is hard to change, near the bottom of its metaphorical valley. But the theory doesn't say much about the world outside the valley.

Since the 1970s physicists have speculated that there could be a lower valley farther out corresponding to an even higher setting for the Higgs field. If it exists, that setting would be the true default, and ours would merely be a "false vacuum"—a temporary value that isn't the one the Higgs field naturally wants to have. In the true vacuum, the Higgs field would be stronger, which would make other fundamental particles such as electrons much, much more massive and harder to create, upsetting the balance that lets atoms exist.

This other valley might seem almost impossible to get to. We would have to roll our metaphorical boulder up another hill before it passed the peak and started to roll down the other side to the lower valley. But quantum physics can make the impossible possible. Through an effect called quantum tunneling, a field can randomly jump from a higher-energy setting to a lower-energy one even if it lacks the energy to climb the hill in between. It's as if it tunneled through the hill rather than traveling over it. If this happened to the Higgs field, it would end our false vacuum and make the true vacuum emerge.



Physicists aren't completely sure what would happen if this change, called vacuum decay, took place. Estimates suggest it would start in a small area, forming a bubble in which the Higgs field sat at its higher setting and all other particles had much higher masses. If the bubble were relatively small, it would wink out, pinched shut by a force akin to the surface tension of a drop of water. If the bubble were big enough, however, the huge difference in energy between the inside and outside would make it start to grow. In empty space, it would expand at the speed of light, changing the Higgs field's setting across the cosmos. "It was all very theoretical until the Higgs boson was discovered," says

Graphics by Jason Drakeford

We do have one key piece of evidence that tells us quite a bit: we're alive.

Matthew D. Schwartz, a professor of physics at Harvard University. Before then, no one knew the mass of the particle.

As a result, physicists weren't sure vacuum decay was even possible. They had a formula to estimate its chance, but it depended on the difficulty of changing the Higgs from its current default setting, which was unknown. The formula said that if the switch were very sticky, our vacuum would be the correct default, not a false vacuum, and would never decay. If it were easy to shift, decay would be much more likely. When the LHC teams announced their discovery of the Higgs particle, we finally had a clear measurement of just how hard it is to shift the Higgs field. For the first time it was possible to calculate how likely vacuum decay should be.

The result was reassuring. In 2017 a team, including Schwartz, calculated a probability of just one in 10^{606} that a vacuum decay bubble would have reached us by now, an absurdly low chance. Imagine taking every atom from all the stars in the sky, giving each one its own universe of stars and then doing that again five more times. Now imagine someone selects one atom at random out of the final total, and you are asked to guess which it is; you would be more likely to pick that specific atom from those universes of universes than to experience vacuum decay.

There is, however, some uncertainty in the calculation, and physicists continue to update their estimates with new data. The formula used to compute the probability of vacuum decay depends not only on the difficulty of changing the Higgs field but also on the mass of other fundamental particles, as well as the strengths of the forces acting on those particles. A 2024 calculation based on more precise measurements lowered the chance even further to around one in 10^{868}.

IT'S POSSIBLE THAT other factors affect the likelihood of vacuum decay. To understand why, think of throwing a pinch of salt into a pot of water just before it boils. When the salt hits the water, the few tentative bubbles that might have been brewing multiply into a froth of activity. If the water wasn't boiling before, it is now. Physicists say the salt "nucleates" bubbles. Each grain of salt can serve as a seed, a little nucleus of change. The rough surface of the salt grains makes it easier for bubbles to form. Soon those bubbles spread until the whole pot is boiling.

As it turns out, what works for bubbles of steam also works for bubbles of vacuum. But you need fancier salt. Specifically, you need black holes.

In 2015 three physicists in England—Ruth Gregory and Philipp Burda, both at Durham University, and Ian Moss of Newcastle University—worked out what was needed. (Others had previously speculated that black holes might trigger vacuum decay, but with data from the LHC it was finally possible to run the numbers.) The U.K. team found that black holes can make vacuum decay dramatically more likely by seeding bubbles in the same way salt does in boiling water. To have an impact, though, the black holes need to be extremely tiny.

Most of the black holes that astronomers see in the universe are dead stars. When the biggest stars reach the end of their lives, they explode in supernovae that create black holes. Left alone, such a black hole will start to shrink. Stephen Hawking figured out that black holes diminish over time, releasing particles called Hawking radiation. This radiation happens because the extreme curvature of space and time around a black hole changes how quantum fields wiggle, turning a momentary jiggling of a switch into a long-lasting particle. Black hole evaporation is extremely slow for big, gently curved black holes, taking much longer than the age of the universe. As a black hole gets smaller, its curves become sharper, causing it to produce more and more particles and to evaporate faster and faster. The smallest black holes evaporate in just a blink of an eye.

Gregory and her collaborators found that the curvier spacetime was around a black hole, the bigger an effect it had on vacuum decay, for much the same reason: strongly curved spacetime makes it easier for quantum fields to change, including the Higgs field. Black holes made from stars are too big, and spacetime around them is too gently curved, to make vacuum decay noticeably more likely. Black holes that are very small won't matter, either, because they evaporate before they have a chance to cause a problem. But black holes that are somewhere in between, with masses of ounces or so, can stir up bubbles.

Making a black hole that small would require compressing an ounce of material into a space many times smaller than a proton, something that can't happen now either technologically or astrophysically. But close to the time of the big bang, black holes might have formed before stars existed as extremely hot, dense matter rippled and cooled. These primordial black holes could have been the right size to seed vacuum decay bubbles, or they could have shrunk to the right size later. Astronomers have searched for evidence of small primordial black holes because they could also explain the mysterious phenomenon of dark matter. So far no evidence for them has been found.

IN 2019 GREGORY TEAMED UP with two U.S.-based physicists, De-Chang Dai of Case Western Reserve University and Dejan Stojkovic of the State University of New York at Buffalo. Together they figured out how many tiny black holes would be needed to destroy the universe. The topic fascinated Stojkovic. "I hate to speculate without calculations, but once you have calculations, as crazy as it looks, you have to face it," he says. "You have to start taking it seriously. What if there is a bubble near Earth? And the bubble is moving with the speed of light, so we'd better calculate this very quickly!"

Once when Stojkovic presented the team's vacuum decay findings at a meeting in Florida, a curmudgeon in the audience asked why he should care. If vacuum bubbles expand at the speed of light, one would hit us before we noticed it was coming. In that case, what use is there in knowing about it?

The question motivated Stojkovic to look deeper. Working with Dai again, as well as Djordje Minic of Virginia Tech, he found that although a vacuum bubble will travel at the speed of light in empty space, it gets slowed down when it encounters massive objects such as stars and planets. This year Stojkovic, Dai and a student of Stojkovic's named Amartya Sengupta published a preprint paper entitled "The Signals of the Doomsday," in which they describe what astronomers might see if such a bubble were nearby: a blast of light with a particular spectrum. What if we see such a signal? "Then you get to decide what to do," Stojkovic says. "I don't know—just go to the beach?"

A more imaginative option was explored by Ashoke Sen, a physicist at the International Center for Theoretical Sciences in Bangalore. In 2015 Sen published an essay proposing that humanity could survive vacuum decay by riding the expansion of space itself. Spacetime is always expanding, and that expansion appears to be speeding up because of a mysterious phenomenon called dark energy. As space pulls apart faster and faster, distant places will be carried apart faster than the speed of light. Sen suggested that if humanity could spread far enough among the stars early enough in cosmic time, it would guarantee that at least some people would escape death by vacuum decay. The expanding universe would drive them apart faster than any onrushing bubble of Higgs-based doom. The paper appeared online on April Fool's Day, but Sen pursued the idea further later that year, which suggests he takes it at least somewhat seriously.

THERE IS A LOT physicists still don't know about vacuum decay. Better measurements from particle colliders could change calculations dramatically, as could finding evidence for tiny black holes. But there is an even bigger mystery, one we probably won't be able to solve anytime soon.

When physicists calculate the chance of vacuum decay, they're using a theory called the Standard Model of particle physics. The Standard Model includes every known particle and describes the results of experiments with remarkable precision. But we know it's incomplete. The model breaks when physicists try to use it to describe particles with an extremely high energy called the Planck energy. If we could collide two protons with this energy, which is roughly equal to the energy in a full tank of gas for a typical car, we couldn't predict what would happen: the Standard Model would give us nonsense.

Something new has to be added to the Standard Model to fix it. Physicists expect there to be new fields: new settings for the universe that we haven't noticed because they take vast amounts of energy to change. These fields would correspond to extremely massive particles that we haven't discovered yet. If these new fields affect the Higgs, though, then all bets are off. The existence of such new fields and particles might change the odds of vacuum decay occurring, and they could even mean there is no second valley for the Higgs after all.

At this point you might think we know practically nothing about vacuum decay. But we do have one key piece of evidence that tells us quite a bit: we're alive. The simple fact that vacuum decay hasn't occurred already—that the universe has been allowed to carry on for 13.7 billion years without an annihilating bubble sweeping through it—puts limits on how likely vacuum decay can be.

Suppose physicists calculated, based on the Standard Model, that there is a 90 percent chance that a vacuum bubble would have found us by now. That might sound scary, but think a minute. Essentially those same odds would have applied to the past as well. A thousand years ago, for instance, we would already have had an 89.999999 percent chance of being hit by a vacuum bubble (the odds then were slightly lower because the universe was slightly younger, meaning a bubble would have had slightly less time to reach us). Clearly, we haven't been wiped out, so that 90 percent calculation can't be the entire story. "The universe would be unstable, and that would mean there would have to be new physics to stabilize it. Otherwise we wouldn't be here," Schwartz says.

Our very existence can teach us something about the laws of physics far beyond what we can test. If physicists calculated a high chance of vacuum decay, and yet vacuum decay still hadn't happened, it would all but guarantee that the Higgs field's faraway second valley has a bundle of new quantum fields in it that the Standard Model doesn't take into account. We can't measure those fields now, and we won't be able to soon. But in a utopian future among the stars, maybe we will. And calculations we do now could tell our descendants where to look. ⬢

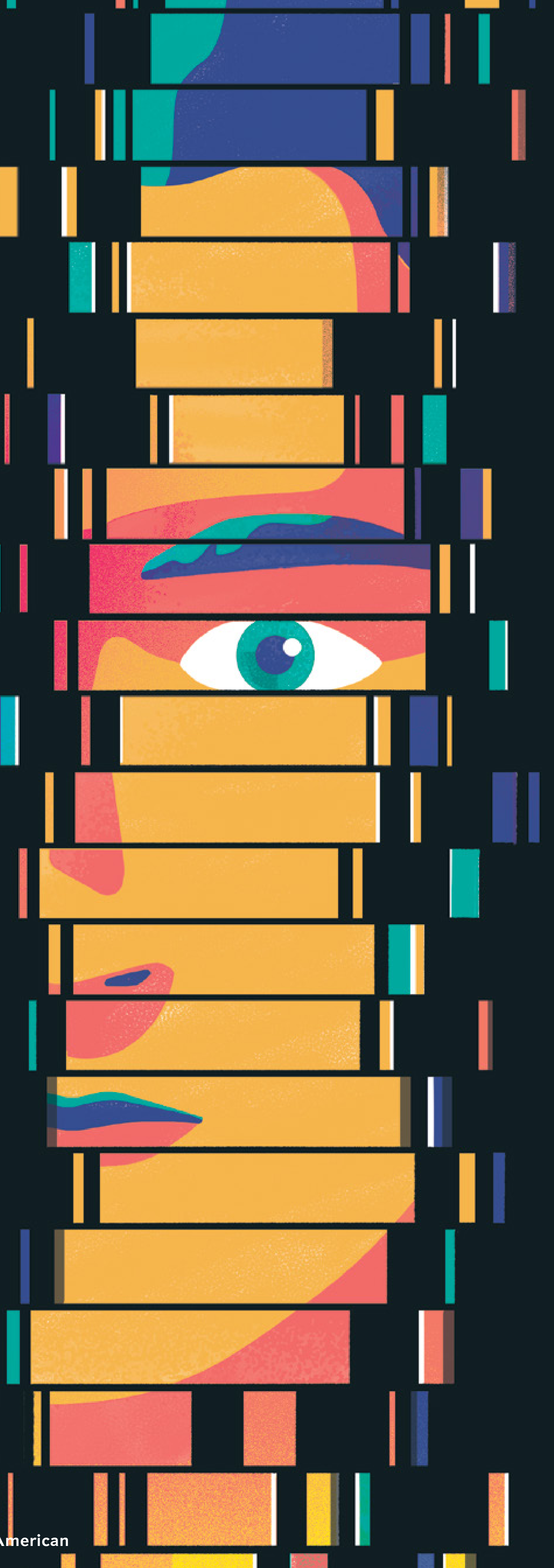
FROM OUR ARCHIVES
The Particle Code. Matthew von Hippel; January 2019. ScientificAmerican.com/archive

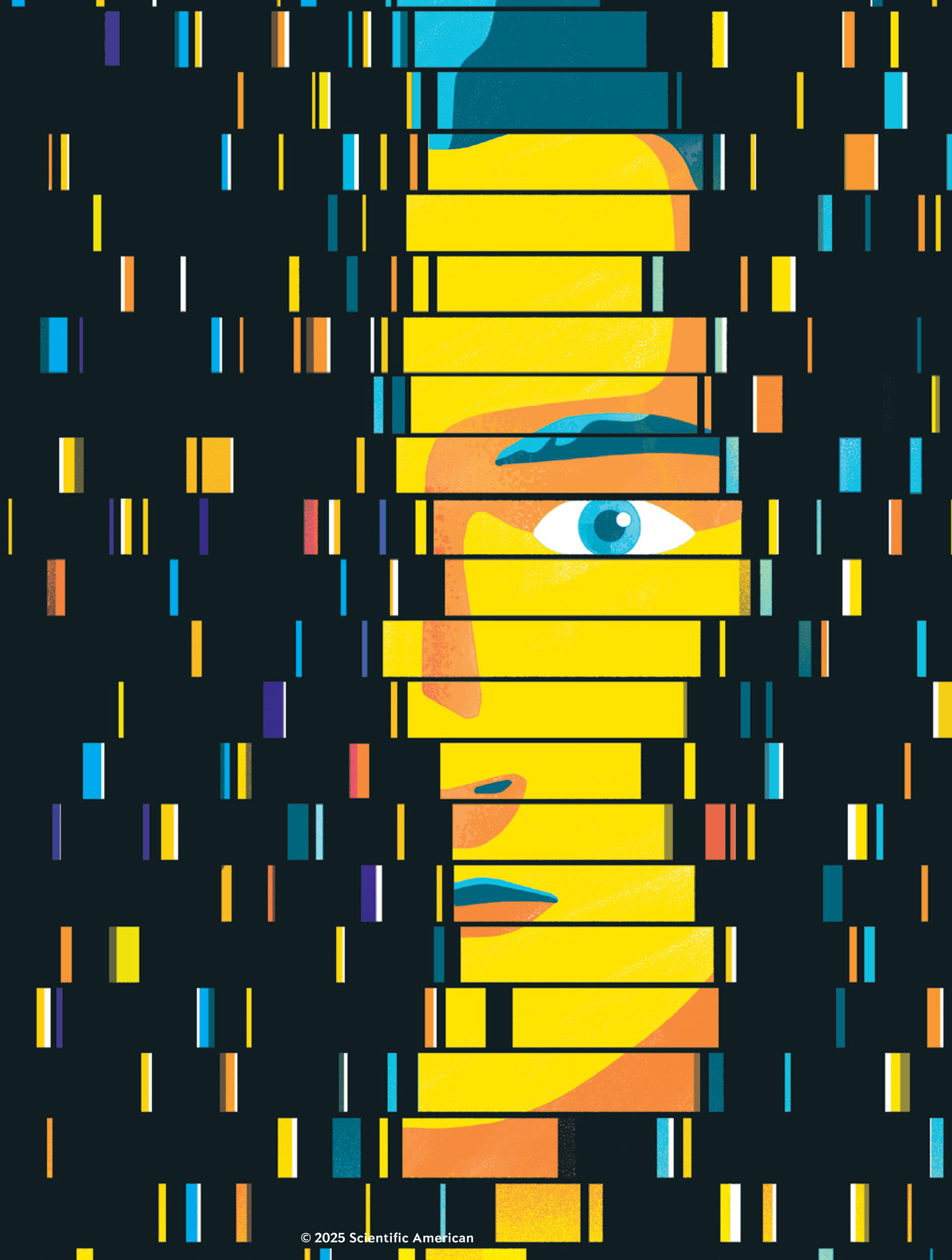
Humans Are Still Evolving

Mounting evidence from genome studies indicates that, contrary to received wisdom, our species has undergone profound biological adaptation in its recent evolutionary past

BY KERMIT PATTISON

ILLUSTRATION BY CHRIS GASH





THE INDIGENOUS PEOPLES OF the Bolivian highlands are survivors. For thousands of years they have lived at altitudes of more than two miles, where oxygen is about 35 percent lower than at sea level. This type of setting is among the harshest environments humans have ever inhabited. Scientists have recognized for some time that these residents of the Andes Mountains have evolved genetic adaptations to the thin air of their lofty home. Now researchers are learning that they have also evolved another remarkable genetic adaptation since their ancestors first settled the highlands of South America around 10,000 years ago.

In the volcanic bedrock of the Andes, arsenic is naturally abundant and leaches into the drinking water. The dangers it poses are well known: inorganic arsenic is associated with cancers, skin lesions, heart disease, diabetes and infant mortality in other populations. But the biochemistry of Andeans has evolved to efficiently metabolize this notoriously toxic substance. Populations in Bolivia—along with groups in Argentina and Chile—have evolved variants around the gene *AS3MT,* which makes enzymes that break down arsenic in the liver. It is a prime example of natural selection, the evolutionary process by which organisms adapt to their environments to survive longer and produce more offspring. Apparently natural selection among the Uru, Aymara and Quechua peoples of the Bolivian Altiplano took DNA sequences that are present but rare in other populations around the world and increased their frequency to the point where the normally uncommon sequences are predominant in these groups. The case is one of many discoveries of relatively recent biological adaptation that could upend a long-standing idea about the evolution of our species.

Kermit Pattison is a journalist and author of *Fossil Men: The Quest for the Oldest Skeleton and the Origins of Humankind* (William Morrow, 2020).

For most of the 21st century many evolutionary biologists have assumed that humans evolved at a leisurely pace in recent millennia, in contrast to the dramatic transformations that occurred earlier in our prehistory. The oldest known members of the human family evolved in Africa around six million to seven million years ago and looked apelike in many ways. Our own species, *Homo sapiens,* arose in Africa a few hundred thousand years ago and began venturing into other parts of the world in significant numbers around 60,000 years ago. By that point our physical appearance seems to have settled into an evolutionary plateau, with only minor differences among human populations around the globe. After natural selection had worked its wonders for millions of years, transforming small-brained quadrupeds into large-brained bipeds, it appeared that biological evolution had slowed to a crawl in our lineage as *H. sapiens* developed agriculture, founded civilizations and transformed the planet.

Early studies of the DNA of modern people turned up few fixed differences—genetic variants possessed exclusively by one population—which seemed to confirm this apparent stasis. Consequently, many scholars believed that the latest chapter of the human saga revolved around cultural changes rather than biological ones—figuring out more reliable means of obtaining food instead of changing our digestive or metabolic systems, for instance.

But advances in the sequencing of ancient and modern DNA have allowed scientists to look more closely at how our genetic code has evolved over time—and the results are startling. Genetic studies suggest that *H. sapiens* experienced many major episodes of natural selection in the past few thousand years as our ances-

tors fanned across the globe and entered new environments containing foods, diseases and toxic substances they had never before encountered. "It shows the plasticity of the human genome," says Karin Broberg of the Karolinska Institute in Sweden, who studies the genetics of susceptibility to environmental toxic substances. "We've spread throughout the world, and we live in very extreme environments, and we're able to make them our homes. We are like rats or cockroaches—extremely adaptable." This research offers fresh insights into how our species conquered every corner of the planet. We didn't manage this feat through cultural adaptation alone, as some scientists previously supposed. Rather humans continued to evolve biologically to keep pace with the radical changes they were making in their ways of life as they pushed into terra incognita.

TO APPRECIATE HOW these evolutionary changes came about, it helps to know the basics of how DNA is structured and how it can vary among individuals and populations. The human genome contains about three billion nucleotide base pairs, the matched sets of two complementary nucleic acids that form the basic unit of our genetic code. The DNA sequences of people today are extremely similar; we differ on only about one tenth of a percent of the genome, or about one out of 1,000 positions. A difference between two people at any position on the genome is called a single nucleotide polymorphism, or SNP (pronounced "snip"). A variant of genetic code—which may be a single position or thousands—that differs between individuals is called an allele. In general, human populations share most of the same genetic variation and evolutionary history.

In Darwinian biology, the classic conception of natural selection is a "hard sweep," in which a beneficial mutation allows some individuals to survive longer or produce more offspring such that eventually that variant becomes fixed in the population. In the early 2000s, when researchers were starting to look for signs of hard sweeps in the genomes of contemporary peoples, the clearest examples came from populations that had adapted to unique circumstances. For instance, around 42,000 years ago a selective sweep changed a protein on the surface of red blood cells in Africans to boost their resistance to malaria. People in the Tibetan Highlands underwent selective sweeps for genes that helped them tolerate low oxygen (intriguingly, populations of the Himalayas, Andes and Ethiopian highlands adapted to high

The Uru people of the Bolivian Altiplano have a gene variant that helps them metabolize the toxic arsenic found in their drinking water.

Gaston Zilberman

altitude with different assortments of genes, taking different evolutionary paths to solve similar problems).

Some of the best-known selective sweeps happened in western Eurasia and involved alleles associated with diet, skin pigmentation and immunity. Many of these sweeps are linked to the profound shifts wrought by the transition to agriculture. Around 8,500 years ago early farmers spread an allele that helped them synthesize long-chain polyunsaturated fatty acids from plant-based foods. These fatty acids are essential for cell membranes, particularly in the brain, and hunter-gatherers obtained them easily from meat and seafood. The new genetic variant allowed agricultural populations to synthesize them from short-chain fatty acids found in plants. This variant was rare at first, but now it is present in about 60 percent of Europeans.

Likewise, as dairy farming rose, so, too, did a gene variant that helped people consume milk products into adulthood. When Stonehenge was built around 5,000 years ago, virtually no Europeans possessed the genes people need to digest milk as adults. In most mammals—and most human populations—the body ceases producing the milk-digesting enzyme lactase after weaning. Yet around 4,500 years ago a gene that kept the lactase turned on in adulthood began to spread through Europe and South Asia. Another series of sweeps beginning around 8,000 years ago gave Eurasians their distinctive pale complexion. These changes reduced their production of the dark skin pigment known as melanin, which is believed to have allowed more sunlight to penetrate their skin and help them synthesize vitamin D, a nutrient in short supply among early agriculturalists.

These examples of hard sweeps became well known among geneticists, mostly because they seemed so uncommon. In the past two decades studies have found that contemporary human populations have relatively few fixed differences. Many researchers thus concluded that selective sweeps accounted for only a little of the genetic change our species has undergone over the past several thousand years. Most of the change, they proposed, stemmed not from natural selection but from gene flow (when populations interbreed as a consequence of migration) and genetic drift (when a genetic variant becomes more or less prevalent through random chance).

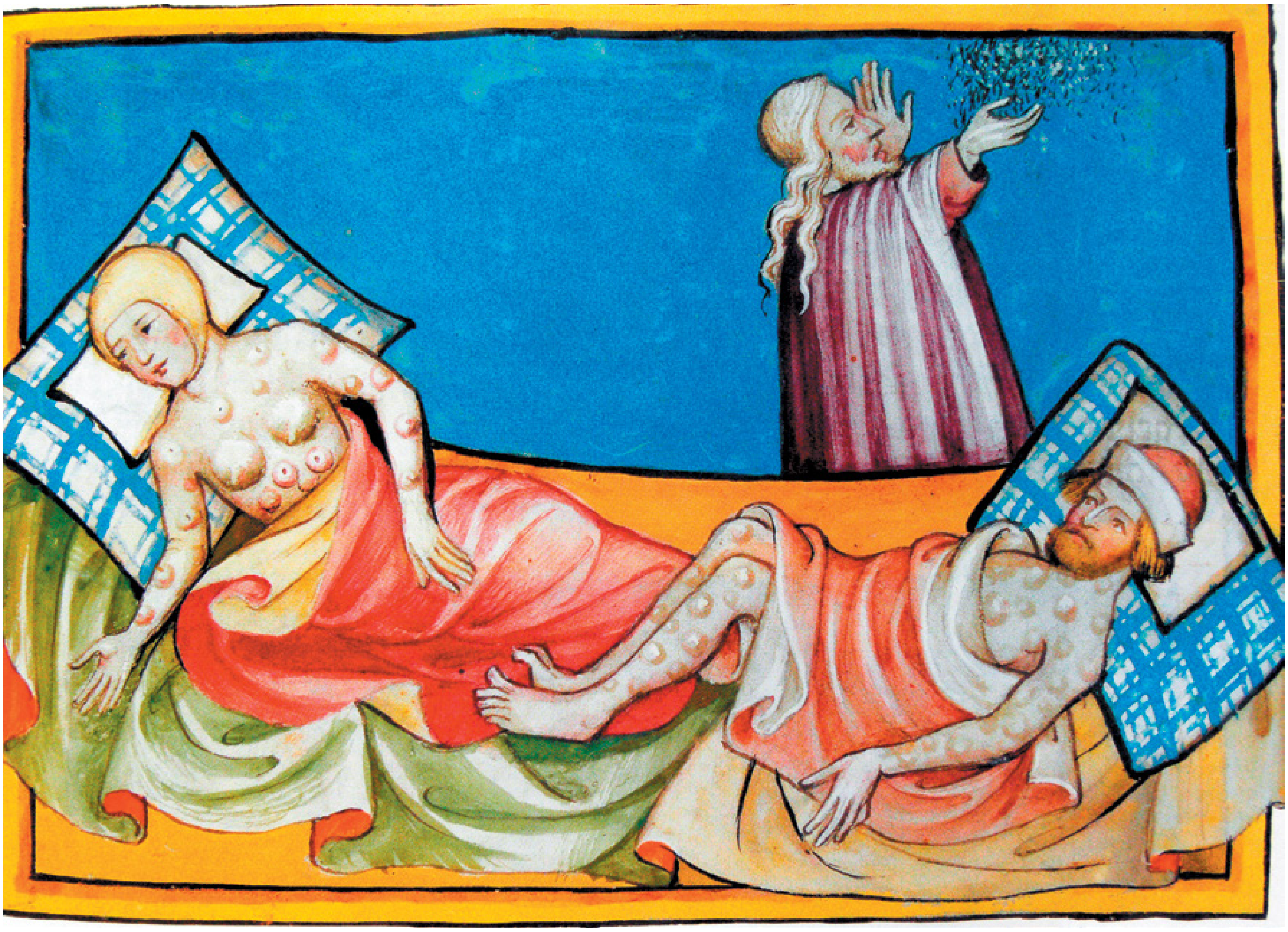
YET RECONSTRUCTING THE PAST from genomes of modern-day people is tricky business because evolution often brushes over its own footprints. Early studies relied on the DNA of modern people to make inferences about evolution, but these methods could detect only events that had lasting effects. Episodes of natural selection are sometimes ephemeral, and evidence of them vanishes from our genomes when the selective pressures subside or when populations mix. Now ancient DNA is allowing investigators to find episodes of long-ago selection that have since been overwritten.

The first ancient human genome was sequenced in 2010. Since then, the number of ancient genomes has expanded steadily to more than 10,000 today. With this growing dataset, researchers can conduct more precise analyses of how the three billion positions in the genome have changed in recent millennia in populations around the world. One 2024 study of ancient DNA tracked the genetic changes in Europe amid major migrations and the transition to farming and pastoralism. Researchers analyzed more than 1,600 ancient genomes spanning the time from 11,000 years ago through the Middle Ages, comparing them with more than 400,000 modern genomes from the U.K. Biobank. When they looked at the modern data alone, they found no instances of selection. But when they examined ancient genomes, they found 11 sweeps. And when they divided those ancient genomes into ancestral lineages, they found 21. The lesson: to fully appreciate the extent of natural selection in history, one must look at local populations in narrow windows of time.

Modern Europeans descend from three main ancestral populations: hunter-gatherers who colonized the continent by around 40,000 years ago, early farmers from Anatolia who came into Europe about 8,500 years ago, and pastoralists from the Pontic-Caspian steppe who arrived around 5,000 years ago. In 2022 a research team led by Yassine Souilmi of the University of Adelaide's Australian Center for Ancient DNA examined 1,162 ancient DNA samples from these ancestral lineages and captured snapshots of their genetics before and after they mixed. They scanned the genomes for any regions with unusually low- or high-frequency alleles, signs of ancient sweeps. They found 57 hard sweeps over the past 50,000 years linked to fat storage, metabolism, skin physiology, immunity and neural function—changes collectively believed to represent adaptations to colder climates. None were shared with a comparative population of sub-Saharan Africans, suggesting they originated after our species began spreading beyond its African birthplace into other parts of the world.

One striking finding was a hard sweep on a region of chromosome 6 called major histocompatibility complex class III, or MHC III, in ancient Anatolians. This ensemble of genes encodes proteins involved in immunity, and natural selection usually promotes genetic diversity in that region to defend against an array of potential threats. In this case, however, the researchers were surprised to find just the opposite—what they called a "distinctive trough of genetic diversity"—in that part of the genome, suggesting that these early farmers were ravaged by disease. "The population had been exposed to something so severe that it wiped out all the diversity that is generally favored in that region," Souilmi says. "It was one of the strongest, if not *the* strongest, adaptation signals we have ever seen in humans."

When the Anatolians later mixed with other populations, however, the MHC III adaptation signal disappeared. The researchers found similar patterns in dozens of other cases from the past 50,000 years. Again and again the selection pressures relaxed, and the traces of adaptations that had been widespread



were "almost entirely erased from descendant populations" through interbreeding with other groups or genetic drift, Souilmi and his co-authors write in their study. "Such strong positive selection events have been much more common in recent human history than previously recognized," they conclude.

This finding contradicts the notion that technological innovation and intelligence exempted later *H. sapiens* from biological adaptation. "It tells us our social fabric and technologies do not necessarily shield us from everything nature has to throw at us," Souilmi says.

ONE THING NATURE REGULARLY THROWS at us is deadly disease. Human populations have long been locked in an evolutionary arms race with pathogens. In a never-ending cycle, disease-causing microorganisms evolve to exploit vulnerabilities in our immune systems, and we adapt to resist these attacks. Even as ancient humans vanquished dangerous predators, they remained vulnerable to these microscopic enemies. For example, the bubonic plague pandemic known as the Black Death, which was caused by the bacterium *Yersinia pestis,* wiped out 30 to 50 percent of the population of Europe in the 14th century.

In this way pathogens helped shape who we are today. "Where there is mortality, there is selection: individuals who die before reaching reproductive age do not pass on their genes," says Lluis Quintana-Murci, a population geneticist at the Institut Pasteur in Paris. "Indeed, infectious diseases and pathogens have been major drivers of natural selection throughout human history."

Those battles became inscribed in our genomes. In a 2023 study, Quintana-Murci and his colleagues analyzed 2,879 ancient and modern genomes to see how the DNA of Europeans changed over the past 10,000 years. They found 139 positions on the genome that had been targeted by strong natural selection—either "positive selection" to promote advantageous genetic variants or "negative selection" to purge harmful ones. These changes largely involved the response to infections. More than 80 percent of the positive selection events began in the past 4,500 years—a time of swelling urban communities, growing dependence on agriculture, proximity to domesticated animals and a rise in epidemics. "Natural selection has been pervasive throughout this period," Quintana-Murci says.

Some adaptations to infectious pathogens came at a cost, however: strengthening resistance to ancient diseases might have elevated the likelihood of immune overreaction. In other words, a hypervigilant defense system could go haywire and attack one's own body. As the risk of infectious disease dropped, the probability

Pathogens such as the bacterium *Yersinia pestis,* which caused the bubonic plague pandemic known as the Black Death, have been major drivers of human evolution.

Niday Picture Library/Alamy Stock Photo

Native Tibetans have a genetic adaptation to the low oxygen levels of their high-altitude home.

of inflammatory and autoimmune disorders appears to have risen. For example, there was a sharp increase in several genetic variants that protect against infectious illnesses but also raise the risk of inflammatory bowel conditions such as Crohn's disease.

Several variants in the MHC (also known as the human leukocyte antigen, or HLA, region in humans) also appear to have undergone selection to resist pathogens. These same variants increased the risk of autoimmune disorders such as ankylosing spondylitis, an inflammatory disease that can cause the vertebrae to fuse, and type 1 diabetes, in which the immune system attacks the cells in the pancreas that make the hormone insulin. Some parts of the genome showed evidence of negative selection as nature weeded out harmful variants. There was a drop in variants that increase the risk of COVID-19, for instance, suggesting that ancient people battled coronaviruses centuries before the recent pandemic.

Taken together, the results suggest that our immune system has been repeatedly tweaked by recent selection like a software system that requires constant updates. Despite the plethora of new discoveries, Quintana-Murci believes researchers have uncovered only the most obvious examples of ancient selection, and he suspects many more cases will come to light as analytical methods become more powerful and researchers obtain more ancient DNA from other regions of the world. "Many surprises are likely to emerge," he says.

ONE BIG SURPRISE is just how pervasive these adaptations have been. A team led by scientists at Harvard Medical School analyzed more than 8,400 DNA samples from people who lived in western Eurasia during the past 14,000 years. They compared these ancient genomes with genetic data from 6,510 modern people and examined nearly 10 million genetic variants. For each SNP, they computed selection coefficients to measure how much natural selection acted to promote or suppress that variant in the next generation.

In a pre-peer-review draft of the paper released publicly last year, David Reich and his colleagues report that they found evidence for natural selection at 347 places on the genome—an order of magnitude more than previously known. The changes were related to immunity, inflammatory responses and cardio-metabolic traits and most likely reflect adaptations to new diets, more crowded living conditions, diseases and domestic livestock.

Reich declined to discuss the results for this story because the paper is currently under review for publication in a journal, but he disclosed that the team expects to expand the number of samples and strengthen

hadynyah/Getty Images

the methodology in the final version of the study. In an interview with podcaster Dwarkesh Patel, Reich previewed the findings and described striking shifts in genetic variants over the past 10 millennia: "We think we have many, many hundreds of places where there [have] been very strong changes in frequency over time," he said. "We think there are many thousands that we can see traces of. The whole genome is seething with these changes in this period."

The preprint of the paper offers examples. Early farming populations underwent strong selection to abandon the "thrifty genes" that promote body-fat storage. These gene variants had been advantageous for hunter-gatherers who endured times of scarcity, but they became liabilities in the more abundant age of agriculture. Other sweeps forged dramatic genetic changes affecting skin pigmentation; blood type; and susceptibility to diseases such as tuberculosis, multiple sclerosis, diabetes, celiac disease, bipolar disorder and schizophrenia.

Like the earlier studies, the Harvard study found a hotspot of activity at the MHC/HLA region of the genome (about 20 percent of the signals came from this area). One allele that increases the risk of celiac disease went from being virtually nonexistent to occurring in 20 percent of the population over the course of just 4,000 years. Presumably this allele offered some as yet unknown protective effect that outweighed its attendant risk of celiac disease.

In many cases, the selection was so strong that the variants would have become universal in the population had the selection continued, but then the pressure waned, and the variants lost their evolutionary cachet. In other cases, the populations interbred with other lineages, and the evidence of past selection was masked.

With new analytical techniques, researchers can read these erasures like an ancient palimpsest. "That's the holy grail—having a really powerful method to detect locations in the genome that are very likely to be under selection," says Ray Tobler, a population geneticist and ancient DNA specialist at Australian National University. "Now the tools we have are very powerful, so we will find a lot more," he predicts.

One promising area of discovery concerns so-called polygenic traits, which are controlled by multiple genes. Most traits and diseases of interest are polygenic. Traditionally they have proved very difficult to study because they can involve the interplay of hundreds or thousands of positions scattered around the genome, each exerting only a minuscule effect on the trait. Human height, for instance, is estimated to be influenced by more than 100,000 positions. Each individual gene involved in a polygenic trait may exert only a small influence on that trait. This distributed influence can make it hard to identify genetic targets of natural selection. "Human adaptation is a polygenic process, usually with small effect sizes of individual genes," says Bing Su, a professor at the Kunming Institute of Zoology at the Chinese Academy of Sciences. But with technological advances that have made it faster and cheaper than ever to sequence high volumes of DNA, he says, scientists now can spot polygenic adaptations that previously were invisible.

New research raises the possibility that recent human history involved far more dynamic evolution than previouly thought.

THESE LATEST GENETIC STUDIES have opened a new frontier in research into traits that are far more complex than the single-gene-mediated ability to digest milk in adulthood. But not everyone agrees that these traits are necessarily products of natural selection. Perhaps, skeptics have suggested, the observed fluctuations in allele frequencies are just routine oscillations of variants in the gene pool rather than proof positive of natural selection acting to adapt the human body to environmental challenges. Some of the papers have drawn criticism about their statistical methods. Some findings of ancient selection have not been replicated by other studies. The numerous papers reporting more natural selection differ on where in the genome it is occurring.

Iain Mathieson, a geneticist at the University of Pennsylvania, is circumspect. He thinks new studies such as the Harvard paper are indeed detecting real shifts in gene frequencies, but he notes that quite a few of them appear to be transient. Mathieson suspects that many genetic variants have been subject to only weak or fleeting selection without much lasting effect. "I mean, that's still selection, but I'm not sure I'd call it directional selection," he says, referring to the type of natural selection responsible for selective sweeps.

Sasha Gusev, a statistical geneticist and associate professor at the Dana-Farber Cancer Institute and Harvard Medical School, takes a different view. The new research raises the possibility that recent human history involved far more dynamic evolution than previously recognized, with repeated episodes of selection followed by reversals. "It's a super interesting question that ancient DNA is opening back up," he says, even if there isn't yet consensus in the field about the extent to which this kind of evolution has occurred.

That consensus may emerge as scientists obtain additional ancient DNA samples and further refine the tools they use to analyze them. The discovery of more hitherto unknown examples of adaptation, meanwhile, seems all but inevitable. Most of the detailed studies of ancient selection have focused on populations in western Eurasia. Much remains to be learned about people in Asia, the Americas, and especially Africa, the birthplace of our species, which holds more human genetic diversity than the rest of the world combined. "While it might seem that we're currently detecting huge amounts of selection, in my opinion we're not detecting enough," Souilmi says. "I think there is a lot more out there." ●

FROM OUR ARCHIVES
Last Hominin Standing. Kate Wong; September 2018. ScientificAmerican.com/archive

Safety Measures Curb Heat-Related Deaths

Extreme, prolonged heat is becoming more common in the U.S., but the government has been slow to respond

BY THE EDITORS

EXTREME HEAT is the number-one weather-related killer in the U.S., causing hundreds to thousands of deaths every year. And available estimates are assuredly undercounts because heat is not always accounted for on death certificates. The need to protect people is becoming clearer and more urgent as heat waves happen more often, last longer and become hotter with climate change.

Fully dealing with the threat would mean tackling systemic issues, from mitigating climate change to rectifying inequities in who is exposed to heat and can afford to cool themselves off. But there are also common-sense protections that could—and should—be put in place by both businesses and our government to prevent heat illnesses and deaths. These changes make economic sense, but more important, they are the humane thing to do.

Extreme heat can cause heat exhaustion (characterized by nausea, dizziness and muscle cramps), heatstroke (an elevated core body temperature, often higher than 104 degrees Fahrenheit, which can damage organs if not promptly treated), and even death. Older people, those with certain health conditions or taking certain medications, and outdoor workers are particularly at risk of heat illness. Outdoor laborers can be especially vulnerable because, in addition to the danger posed by the ambient heat, their work often raises their body temperature.

The U.S. Bureau of Labor Statistics documented 34 heat-related deaths of workers per year between 1992 and 2022, as well as an annual average of 3,389 injuries and illnesses that caused people to miss days of work between 2011 and 2022. And an examination of workers' compensation claims in California that included more cases than just those where people missed work found three to six times the number of illnesses and injuries compared with the Labor Bureau's records for that state.

A few states, such as California and Oregon, have enacted protections for workers following the rubric of "water, rest, shade"—workers should have ready access to drinkable water and ample rest breaks, ideally in air conditioning and at least in shade, to allow the body to cool and recover. The physiological science behind these interventions is clear, and formal protections requiring these measures have worked.

But piecemeal state legislation leaves many workers unprotected. Scientists and policymakers have argued for a federal standard set by the Occupational Safety and Health Administration (OSHA) since the agency's inception in the 1970s. In 2024 OSHA finally proposed a rule that would require not only access to water, rest breaks, and shade or other cooling areas but also heat safety training and protocols to acclimatize new and returning workers to high-heat conditions. As with many rules proposed late in the Biden administration, its fate depends on the Trump administration's willingness to put the safety of the American population first.

The current administration should see this rule through—and maintain robust OSHA staffing to enforce it—because it would not only avert highly preventable deaths but also improve economic productivity. Research shows that unrelieved exposure to high heat impairs concentration, coordination and decision-making. If we want people to do their jobs optimally, we should give them the protection they need to do so.

Some businesses have opposed heat health rules, arguing that they impose expenses and that people should be responsible for themselves—an Oregon farm company made this argument after the death of one of its workers before the state enacted its heat safety law. But most of these measures are relatively inexpensive. In addition, heat illness is notoriously difficult for anyone to recognize in themselves, and as a vulnerable class, laborers sometimes avoid taking voluntary breaks for rest or water because they believe doing so will make their bosses think they aren't hard

Illustration by Pete Ryan

workers and might cost them their jobs.

Existing state rules and the proposed OSHA standard give businesses flexibility in implementing protections: farms may need to have mobile hydration and cooling stations, whereas an oil and gas facility might be able to erect permanent shaded areas for its workers. The goal is to keep people safe, not to impose rigid burdens on businesses.

For these reasons, it would actually be in the economic interest of companies, especially ones that operate in multiple states, to lobby the administration to maintain the rule so they can avoid the patchwork of requirements across the country (although states would still be allowed to institute stricter rules on their own).

In 2015 California strengthened its rules about worker protection and saw positive changes. Part of this success was the result of better enforcement. That is another reason to put an OSHA heat safety standard in place: a specific standard would greatly simplify enforcement. Under a current rule known as the General Duty Clause, the agency must go employer by employer and meet a list of criteria to enforce action.

If the Trump administration does not keep the federal rule, states must be ready to step into the breach to protect workers. They need not reinvent the wheel—the proposed OSHA rule, as well as regulations passed in states such as California and Oregon, could be readily adapted to other places.

Further, states such as Texas and Florida that have passed laws banning local jurisdictions from enacting heat safety regulations must reverse course. Texas and the Southeast have seen some of the largest increases in the number of days when heat and humidity rise to dangerous levels, meaning workers in those states are protected only if they are fortunate enough to work for a company that voluntarily provides adequate safety measures. Protecting people, not just businesses, is the government's job.

Providing access to very basic cooling measures is an overall inexpensive way to keep people safe and has the side benefit of economic efficiency. As Sharon Block, a Harvard Law School professor and labor lawyer, puts it, "it's not just the decent thing to do but the smart thing to do." ■

Genetic Genealogy Can Exonerate the Innocent

Investigative genetic genealogy has been underused as a tool to help free the wrongly convicted

BY DAVID GURNEY AND JAMES R. MAYER

SINCE 1989, 3,615 people convicted of crimes in the U.S. have been exonerated and freed after their conviction was reversed. Post-conviction DNA testing played a part in 606 of these cases.

Brothers Robert and David Bintz became new additions to this list last September after investigative genetic genealogy (IGG)—which relies on genealogical and genetic data to reverse engineer family trees—helped to reveal the true perpetrator of the 1987 crime they had been convicted of. In many ways, their cases are typical of other wrongful convictions: false confessions and jailhouse informants provided the primary evidence against them at trial. Yet their stories are unusual because of the underlying investigative method essential to their exonerations.

The Bintz brothers are only the third and fourth individuals cleared with the help of IGG. Although the revolutionary investigative technique has, since its inception in 2018, been used primarily to identify human remains and perpetrators of violent crimes, the dual exonerations of the Bintz brothers demonstrate its power as a tool of justice generally. It's one that more wrongful-conviction organizations should pursue. This case is also a testament to the need for legislative reform to address injustices in the criminal legal system, particularly for those who are found innocent after serving time in prison.

On August 3, 1987, Sandra Lison—a mother of two—disappeared from the Good Times Tavern in Green Bay, Wis., where she worked as a bartender. The following morning hikers discovered Lison's body in a nearby forest. She had been strangled, and police noted the presence of semen, which was later found to be a DNA match to a blood spot on Lison's dress. For 11 years law enforcement was unable to identify a viable suspect in the case.

Then, in 1998, while David Bintz was serving time in prison for an unrelated crime, his cellmate claimed David had made incriminating statements about Lison in his sleep. The cellmate (and others) said David also implicated his brother, Robert. Under interrogation, David confirmed the statements but also denied involvement in the crime. Law enforcement reviewed notes from the initial investigation and discovered that David and Robert had bought beer from Lison on the night of her disappearance and had been upset about the price difference between a case of beer and four six-packs. With David's alleged confession and this motive as evidence, the brothers were tried for Lison's murder.

Prosecuting attorneys in the Bintz brothers' trials knew that the only DNA evidence in the case, which came from semen and blood on the victim, excluded Robert and David. Thus, they argued that both substances were unrelated to Lison's death. Despite the absence of physical evidence tying them to the scene, the brothers were each convicted and sentenced to life in prison.

In 2019 the Great North Innocence Project (GNIP) took on the case of Robert Bintz, convinced that the DNA evidence from the crime scene was the key to his exonera-

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James R. Mayer is legal director of the Great North Innocence Project.

tion—and to the identification of the true perpetrator.

Just a year before, IGG had made headlines for helping to identify Joseph James DeAngelo as the Golden State Killer and Marcia King as the Jane Doe previously known as Buckskin Girl. GNIP had followed the development of IGG as it played a role in the 2019 exoneration of Christopher Tapp, who had served 20 years after a wrongful conviction for murder, and the group recognized its potential to help the Bintz brothers.

Working with forensic technology firm Bode Technology, GNIP developed an advanced genetic profile from the crime scene evidence. That profile was uploaded to two consumer genetic genealogy databases, FamilyTreeDNA and GEDmatch, where members of the public can upload their DNA information for personal research. A subset of those individuals have opted to allow their data to be compared with crime scene profiles and those developed from unidentified human remains.

In the summer of 2023 GNIP turned this work over to the Ramapo College Investigative Genetic Genealogy Center, which was founded in 2022 partly to apply the powerful investigative tool of IGG to more cases of wrongful conviction. In just two days a small group of staff and students in the center's inaugural "IGG Bootcamp" reverse engineered the family tree of the individual who had left the DNA at the crime scene in Green Bay 36 years earlier. The team traced the family tree and landed on three brothers who fit all the genetic and genealogical evidence. One brother stood out: William Hendricks, who had been convicted of rape and had been released from prison just seven months before Lison's murder.

The dual exonerations of the Bintz brothers in Wisconsin demonstrate investigative genetic genealogy's power as a tool of justice.

Hendricks died in a mental hospital in 2000. In the summer of 2024 his body was exhumed, and ultimately Bode Technology developed a genetic profile from his remains. When it was compared with the crime scene evidence, the result was unequivocal: William Hendricks had left the blood and semen on Lison. Investigators in Wisconsin went back to the evidence in the case and discovered that fingerprints on an empty cigar box found behind the counter at the Good Times Tavern matched Hendricks as well.

There could no longer be any doubt about who raped and murdered Lison. Last September, Wisconsin prosecutors joined GNIP and the Wisconsin Innocence Project (which represented David) in seeking the release and exoneration of the Bintz brothers. Within days they walked out of prison.

There are many similar cases that IGG could help resolve, yet concerns about the technique may be slowing its adoption for this purpose. Skepticism of any new investigative or forensic method is justified, but the questions raised about IGG have largely been answered. Today there are a host of IGG practitioners and teams who have developed robust policies and procedures around use of the technique. The Investigative Genetic Genealogy Accreditation Board has promulgated standards and a code of ethics for the field and will soon offer an accreditation exam, as well as a database of those who have passed the exam and met other requirements.

For the Bintz brothers, the path forward will not be easy. Unlike prisoners who are released after serving their full sentence, those who are suddenly exonerated don't have access to any services that could ease their reentry into free society. And for their quarter of a century in prison, Robert and David will each receive compensation of just $25,000, the limit allowed by Wisconsin law. The Innocence Project recommends, and many states provide, a minimum of $70,000 per year served.

We encourage attorneys fighting to free the innocent to embrace IGG, and we urge the Wisconsin legislature to use the lesson of these cases to align the state's compensation statute with the amount recommended by the Innocence Project. ●

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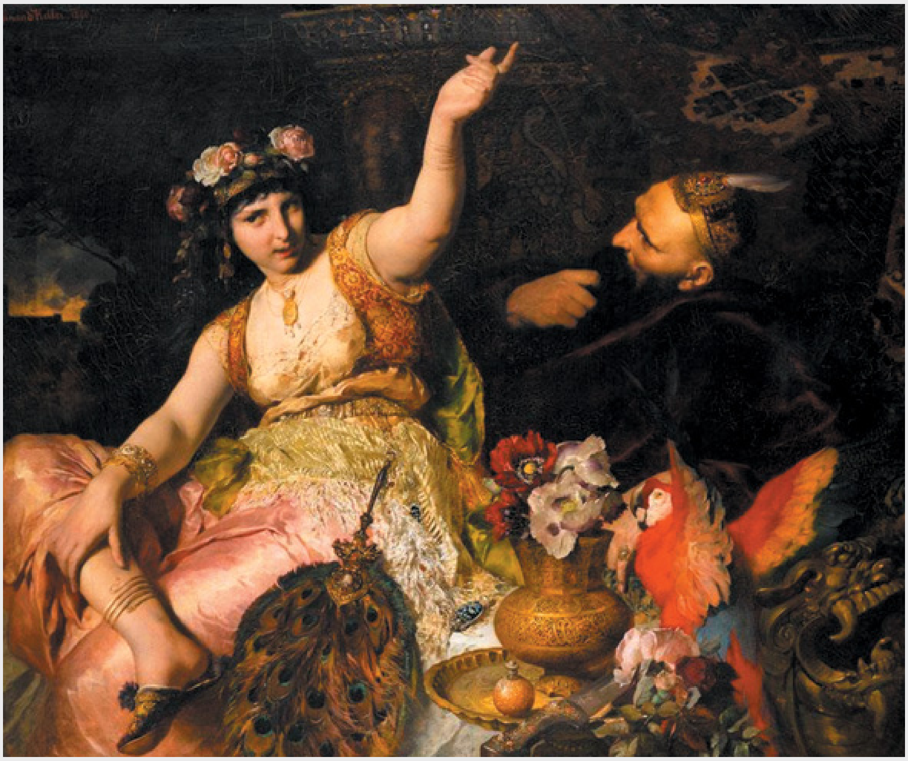

The Power of Storytelling

Good storytellers are more likely to have a sense of purpose and to see the big picture

BY RON SHACHAR

KING SHAHRYAR, betrayed by his wife, decides to marry a new woman each night and have her executed by morning to ensure he is never deceived again. After Scheherazade volunteers to marry the king, she outsmarts him. She begins a gripping story every evening but stops telling it at dawn, leaving her husband eager for more. Night after night she keeps him hooked with new tales, and over the course of 1,001 nights he falls in love with her and abandons his cruel ways.

This story is the frame of *One Thousand and One Nights,* a medieval collection of Middle Eastern folktales—including the stories of Aladdin, Ali Baba and Sinbad—that highlight the power of storytelling. But can storytelling skills indeed save a person's life in the real world?

The findings of recent research by my colleagues and me don't go that far yet, but they do show that strong storytelling skills can dramatically improve someone's well-being. This result hints that, yes, skillful storytellers may actually live longer. How, exactly? You'll have to wait until the end of this story to find out. No peeking!

Our journey starts with extensive research on narrative identity showing that people make sense of who they are by shaping their life experiences into a story—one that gives their life meaning. The idea is that by connecting our experiences, we can recognize the guiding force that has shaped our journey (for instance, the belief that we like helping people) and, in turn, uncover our sense of purpose and meaning in life.

In our research, my colleagues and I shift the focus from stories, particularly life stories, to storytelling. We suggest that compared with others, skillful storytellers have a stronger sense of meaning in life and approach their experiences with what we call a "why mindset"—that is, they focus on their reasons for doing what they do rather than just on how they do it.

Our hypothesis about storytellers is rooted in the nature of stories. The typical narrative focuses on a hero who strives to achieve a goal, such as landing a job or winning someone's heart, while facing various obstacles and challenges along the way. Therefore, to excel at storytelling, individuals must develop two key skills. First, they need to connect the dots—the events of the story—in a meaningful way to create a coherent narrative. Second, they must learn to see the world through the eyes of their characters, understanding the why of what drives people. In applying these two skills to their own lives, talented storytellers use the first to identify and pursue what gives their life meaning and the second to foster a mindset that prioritizes the why behind their actions over the how.

To illustrate this point, let's imagine two people: Rachel and Monica. Both had the same career path, and both worked in multiple, vastly different industries, including sports, medicine and banking. Throughout their careers they often acted on impulse. Rachel is a skillful storyteller, however, and Monica isn't. This difference comes across vividly when they reflect on their careers. Monica is more likely to feel lost and to lack clarity about her sense of meaning and purpose in life because she doesn't possess a why mindset, having always focused on how to get things done rather than the bigger picture. Rachel, in contrast, is inclined to reflect more deeply on her life and see connections, such as the fact that in all her managerial jobs she used her position to bolster the presence of women in decision-making roles. This observation gives her a sense of purpose and a deeper understanding of what drives her—that is, her why. But this story is just hypothetical. Does it pan out in real life?

To examine how a skill for narrative serves storytellers,

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History and Art Collection/Alamy Stock Photo we conducted five studies with about 800 participants. To reliably measure storytelling ability, we took a multifaceted approach. First, we developed and tested a questionnaire in which we asked people how much they agreed with statements such as "my stories usually excite my listeners." Second, we interviewed close friends of the participants about their storytelling skills. Third, we invited trios of strangers to our laboratory and asked them to share stories with one another. In our lab experiment, each participant told two distinct stories: one about a personal trait and one that incorporated three random words we provided, a task designed to isolate the core mechanics of storytelling.

This approach is a significant departure from previous studies of life stories—here we are really homing in on the ability to craft a compelling narrative from minimal material. As part of the experiment, each participant rated the storytelling ability of the others in their trio, and afterward storytelling experts—people who had just completed a course on the subject—reviewed video recordings of the sessions and provided independent ratings. Thus, we had four measures of storytelling skill: (1) people's self-reports of their own ability, (2) opinions of close friends, (3) ratings from other members of the trio in our lab experiment and (4) evaluations from storytelling experts. In addition to these assessments, we asked participants questions to get a sense of how meaningful they found life and whether they approached decisions with a why mindset rather than a how mindset.

Across all studies and measures, we consistently found that storytelling ability is linked to both a sense of meaning in life and a mindset focused on the whys. When we tested whether personality traits might be driving our findings, we found they weren't. That said, personality did add interesting nuance. People who are naturally open to new experiences tend to be better storytellers, for example. That makes sense: such people are more likely to be part of unique and interesting events that lend themselves to great stories, and these encounters give these individuals more opportunities to refine their storytelling skills as they share their experiences with others.

We also found that storytelling skills related to meaning in life for introverts more than they did for extroverts. In general, extroverts have a stronger sense of meaning in life, but storytelling may help introverts compensate for that difference. Both storytelling and extroversion are related to expressiveness. Extroversion is all about the urge to express yourself in social settings, whereas storytelling is about having a knack for doing so through stories. It turns out that either one of these tendencies can be enough to spark a sense of meaning and purpose.

This work offers several lessons. First, because people with a why mindset, by definition, excel at seeing the big picture, our findings suggest that the abilities to tell stories well and to see the big picture are closely related. Although seeing the big picture is useful in its own right, it may also be a crucial advantage that humans have over artificial intelligence, which excels at executing micro tasks. Thus, when we are facing an uncertain future, our ability to tell stories is something we should treasure and cultivate.

My team's findings also suggest that storytelling workshops—which have grown popular in recent years—influence people's lives in ways that go beyond improving communication and persuasion. They may strengthen the driving force of our existence and sharpen our sense of direction in life.

The benefits of cultivating greater purpose are many, and some of them are unexpected. Past research has found that a strong sense of meaning in life is associated with many health benefits, including a longer lifespan. Combined with our findings, this outcome suggests storytelling may also contribute to better health and decreased mortality. Plus, storytelling helps people connect, which can naturally expand their social circles. Because strong social relationships are known to boost health and even influence longevity, it makes sense that storytelling could indirectly support physical health by fostering deeper and broader social ties.

Perhaps *One Thousand and One Nights* was correct all along: storytelling may help save your life. ●

Voting to Change the Value of Pi

How an incorrect value of pi almost got codified into law

BY JACK MURTAGH

AN AGE-OLD PROBLEM known as squaring the circle stumped mathematicians for more than 2,000 years. During that time, professionals and amateurs alike unknowingly published thousands of false proofs that they claimed resolved it. False proof attempts are natural stumbling blocks on the road to mathematical progress. They tend to fall by the wayside, either when peers uncover flaws in expert research or when crank arguments fail basic smell tests for legitimacy. But one didn't fade quietly. Instead it forced a volunteer mathematician to tutor state senators, sparked media ridicule and nearly got an incorrect value of pi (π) codified into law.

Here's the problem that has consumed ancient Greek mathematicians and countless others: given a circle, construct a square with the same area as it using only a compass and straightedge. You may remember compasses from school. They let you take any two points and draw a circle centered at one of them and passing through the other. A straightedge helps you draw straight lines; it's like a ruler without measurement markings. As the founders of the geometric proof, the Greeks placed special emphasis on the ability to draw, or construct, their objects of study with these simplest-possible tools.

The task seems straightforward, but a solution remained surprisingly elusive. In 1894 physician and mathematical dabbler Edward J. Goodwin believed he had found one. He felt so proud of his discovery that, in 1897, he drew up a bill for his home state of Indiana to enshrine what he thought was a mathematical proof into law. In exchange, he would allow the state to use his proof without paying royalties. At least three major red flags should have prompted lawmakers to regard Goodwin with skepticism. Math research has no norm about charging royalties or precedent for legally ratifying theorems, and the supposed proof was nonsense. Among other errors, it claimed that pi, the ratio of a circle's circumference to its diameter, is 3.2 rather than the well-established 3.14159.... Yet, in a bizarre legislative oversight, the Indiana House of Representatives passed the bill in a unanimous vote.

Why would politicians enact hogwash and sully their sterling reputation for passing fact-based policy? In their defense, they seemed confused about the bill's contents and played hot potato with it, tossing it to the Committee on Canals, which flung it over to the Committee on Education. They held three formal readings of the bill before voting. Goodwin had also managed to publish his work in the *American Mathematical Monthly,* a highly reputable journal to this day. This probably made him seem credible to outside eyes, even though the journal had a policy back then of uncritically publishing all submissions with a "by request of the author" tag. Perhaps Indiana's House of Representatives wanted to punt the problem to the state senate to determine the fate of the imperiled constant.

In 1897 the *Chicago Tribune* wrote that "a circle originating in Ohio will find its proportions modified as soon as it lands on Indiana soil."

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As if this story weren't outlandish enough, Goodwin's endeavor to square the circle was doomed from the start: German mathematician Ferdinand von Lindemann proved the task impossible in 1882. Furthermore, Lindemann's argument explains why so many false proofs of squaring the circle hinge on erroneous values of pi.

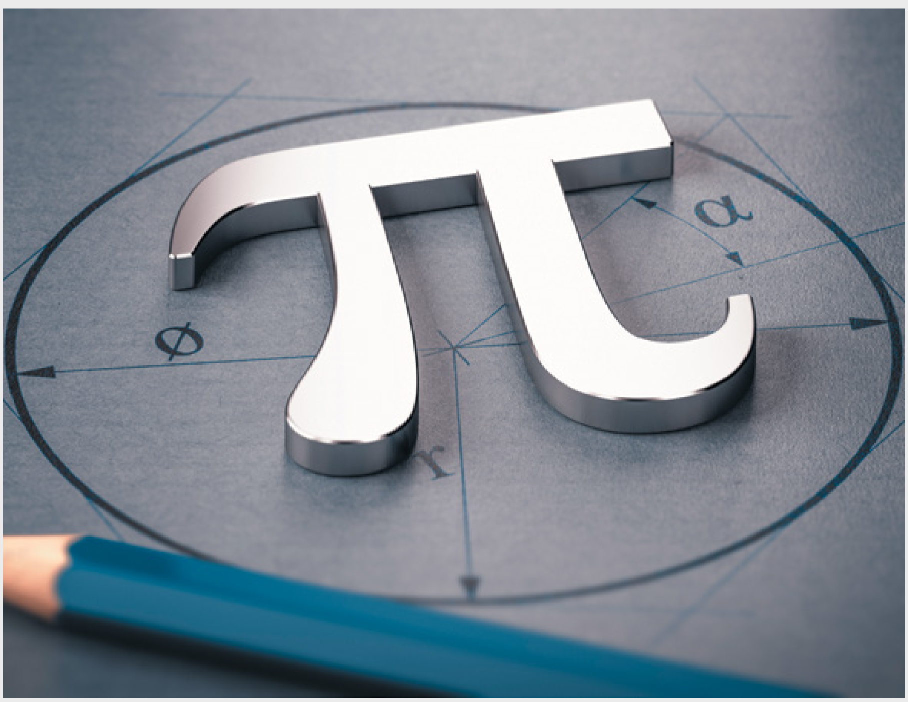
To see how, consider a circle with radius 1. When we calculate its area as $A = \pi r^2$, that circle has an area of π. A square—whose area is calculated as the square of the length of one side—would need sides of length $\sqrt{\pi}$ for its area to equal the circle's. So the great geometric puzzle of antiquity boils down to this question: Given a reference length of 1 unit, can you draw a line segment of length exactly $\sqrt{\pi}$ using only a compass and straightedge? If you can, then finishing the other edges of the square at right angles is the easy part. Hordes of mathematicians wrestled with this problem, and although nobody resolved it, they had made significant progress by the time Lindemann stepped in.

By then the math community knew it was possible to construct only certain lengths. Strangely, you can construct a line of some given length with a compass and straightedge only if that length can be expressed in integers and by using the algebraic operations of addition, subtraction, multiplication, division and square root. Thus, the simple tools of the Greeks can be used to construct some highly complicated numbers, such as this one:

$$\sqrt{3/8 \times \sqrt{2/\sqrt{13/15}}}$$

But those tools can't help us construct comparatively simple numbers such as the cube root of 2 (the number that, when multiplied by itself three times, equals 2) because there is no way to express it in terms of the five permissible operations alone.

Lindemann proved that pi is a transcendental number. This means that not only do $+$, $-$, $\times$, $/$ and $\sqrt{\ }$ fall short of expressing it, but even more exotic operations such as cube roots, fifth roots, and so on wouldn't help. Lindemann extended earlier work by French mathematician Charles Hermite, who had demonstrated that another famous constant, e (Euler's number, 2.71828...), is transcendental. Though entwined with geometry's simplest shape, pi cannot be expressed with algebra's simplest language. Because pi is not a constructible length, neither is $\sqrt{\pi}$, rendering the task of squar-



Olivier Le Moal/Getty Images

ing the circle impossible. The discovery even seeped into idiomatic language. Today "squaring the circle" means attempting the impossible.

These insights also explain why Goodwin could seemingly achieve the unachievable after assuming that pi equals 3.2. We can write 3.2 as 16⁄5, which clearly uses only integers and division. By substituting a neat, rational number for pi, Goodwin sidestepped the fundamental difficulty of the problem.

Of course, nobody in the Indiana state government in 1897 knew any of this. Having passed the state house sans a single dissenting vote, the bill was a state senate hearing away from upending the foundations of math by fiat. By pure coincidence, the head professor of math at Purdue University, Clarence A. Waldo, happened to visit the statehouse just when lawmakers needed him. Waldo, who had come to lobby for his school's budget, overheard a mathematical discussion. Appalled at the proceedings, Waldo resolved to derail the bill. He stuck around to educate the state senators on geometric matters, hoping to end the farce. At debate time, the senators came equipped with Waldo's tutelage and probably felt pressured by media attention, given that news outlets had begun to cover the story in an unflattering light.

An editorial in the *Chicago Tribune* brimmed with scathing sarcasm:

> The immediate effect of this change will be to give all circles when they enter Indiana either greater circumferences or less diameters. An Illinois circle or a circle originating in Ohio will find its proportions modified as soon as it lands on Indiana soil.... A Pi that is so simple as 3.2 ought to be free from any entangling features, but if perchance it still proves obdurate no doubt the Legislature will promptly lop off another decimal and call it 3.

Indiana's senate didn't vote down the bill. The state senators did, however, agree to postpone it indefinitely. Had it not been for a mathematician in the right place at the right time, they might have continued to go around in circles. ●

The Secret to Animal Consciousness

Emotions—including joy—may be key markers of conscious beings

BY JACEK KRYWKO

RATS LAUGH, BEES ROLL BALLS for fun, turtles dance when they anticipate feeding, and dogs wiggle their tails when they're excited. Research into animal emotions and experience has been on the rise since the late 20th century, and scientists are beginning to use these findings to answer an age-old question: Do nonhuman animals have consciousness?

Consciousness is often defined as the ability to have subjective experiences. "We are focusing on this particular kind of phenomenal consciousness—that it feels like something to be you," says philosopher Jeff Sebo, director of the Center for Environmental and Animal Protection and of the Center for Mind, Ethics, and Policy, both at New York University. "If you can have subjective feelings, either sensory experiences like perception or affective experiences like pleasure or pain, that is what we call consciousness."

Sebo, along with philosophers Kristin Andrews of York University in Toronto and Jonathan Birch of the London School of Economics and Political Science, initiated the New York Declaration on Animal Consciousness. Since its release in April 2024, it has been signed by more than 500 scientists and researchers worldwide. The same trio recently coauthored an essay in the journal *Science* arguing that when animals engage in behaviors similar to those that are explained by conscious experience in humans, such as demonstrations of joy, suffering, and other emotions, that can begin to suggest animals' conscious experience, too.

SCIENTIFIC AMERICAN talked with Sebo about what the potential markers of consciousness are, whether we should assume a species is conscious unless proven otherwise, and how scientists might study consciousness through signs of animal joy. *An edited transcript of the interview follows.*

How can looking for markers of joy or pain help us determine whether animals are conscious?

Consciousness is such a difficult topic to study. It confronts us with the hard problem of explaining why any physical system, including our own brain, should be conscious, as well as the problem of other minds—the problem that the only mind I can directly access is my own. That makes it hard for me to know for sure what, if anything, it feels like to be anyone else, even other humans. So instead of attempting to solve the hard problem of consciousness or the problem of other minds, we identify behavioral and anatomical markers that are consistent with a range of leading scientific theories of consciousness, and then we search for those markers in animals.

You would start by using introspection to distinguish between conscious and unconscious experience in humans. We can look inward and tell when we are experiencing conscious pain versus having an unconscious nociceptive response. We then look for observable behavioral or anatomical markers or indicators that are associated with conscious processing in humans, and we can then look for broadly analogous behavioral or anatomical indicators in animals.

Obviously, they are not going to be proof of consciousness. They are not going to establish certainty about consciousness, but we can treat them as evidence. And when we find a lot of markers together in an animal, that can take up the probability that consciousness is present.

So the final step would be to estimate at least a rough probability of consciousness based on how many behavioral and ana-

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tomical markers we find in that animal. Establishing high, medium, even low probability of consciousness can be a helpful step toward making informed decisions about how to study that animal or how to interact with it.

How should we deal with this lack of certainty? Should we assume that an animal is conscious until proven otherwise or that it is not until we find enough consciousness markers?

Typically scientists assume that consciousness is absent unless evidence demonstrates it is present. But if such a vast number and wide range of animals now have at least a realistic possibility of consciousness based on existing evidence, then it does raise the question of whether we should instead have a neutral starting point or proceed on the assumption that consciousness is present unless a lot of evidence indicates it is absent.

My colleague Kristin Andrews, who wrote the *Science* essay with Jonathan Birch and me, has argued that we in fact should flip the default assumption to the presence of consciousness in animals—that we should presume animals are conscious and then research the dimensions of that consciousness.

Andrews argues that this assumption is good not only ethically, because it represents a kind of precautionary stance toward our interactions with animals, but also scientifically, because it leads to better and more rigorous hypotheses about the nature of consciousness and the dimensions of consciousness that we can then research.

You suggest animal consciousness research is overly reliant on pain markers—intentionally inflicting pain to see how animals respond to it. Does presuming consciousness complicate this practice?

We use pain markers to assess the probability that particular animals can consciously experience negative states such as pain and suffering. You can ask basic questions: Do they nurse their own wounds? Do they respond to analgesics or antidepressants in the same ways that humans do? Do they make behavioral trade-offs between the avoidance of pain and the pursuit of other valuable goals such as finding a new shell or finding food? And if they do behave that way, we can become more confident that they can experience pain and suffering. This knowledge gives us information about how we might change our interactions with them in ethics and policy.

But if animals have a realistic chance of being conscious, there should be ethical safeguards regarding how pain markers are used. We can look at past studies investigating the presence or absence of pain markers. We can also conduct observational field research and use observations of animals experiencing pain and nursing their wounds in the wild without intentionally inflicting pain. We can still use pain markers if we collect them ethically.

The advantage of using pain markers is that they are easy to observe. How do you study joy?

There are at least some markers of joy that appear to be quite widespread across animals. One is vocalizations that resemble laughter. Quite a few species will vocalize in a way that indicates joyful experience. Rodents can vocalize ultrahigh-frequency sounds in response to play or tickling in a way that resembles laughter.

Another example is optimism. You can perform studies that give animals the opportunity to pursue the unknown. If they pursue it more readily, then that suggests an optimistic outlook. If they pursue it less readily, then that suggests a pessimistic outlook. Optimism is generally associated with positive experience, positive affect.

Then there is play. We see play behavior in a lot of different animals. It does not have an obvious direct evolutionary advantage, but it seems to be an expression of joy. We find that not only in other mammals, such as dogs, but even in insects. There is research involving bees rolling a ball around for no reason other than the kind of positive experience associated with it.

Other joy markers are more species-specific, such as facial expressions or tail-wagging. Finally, the presence of oxytocin or dopamine or serotonin in the brain may serve to indicate joy.

Combined with markers of pain and perception, markers of joy can give us a better understanding of consciousness. If animals have a realistic chance of being conscious, then we have both ethical and scientific reasons to look beyond pain. ●

Illustration by Shideh Ghandeharizadeh

Light Touch

By Aimee Lucido

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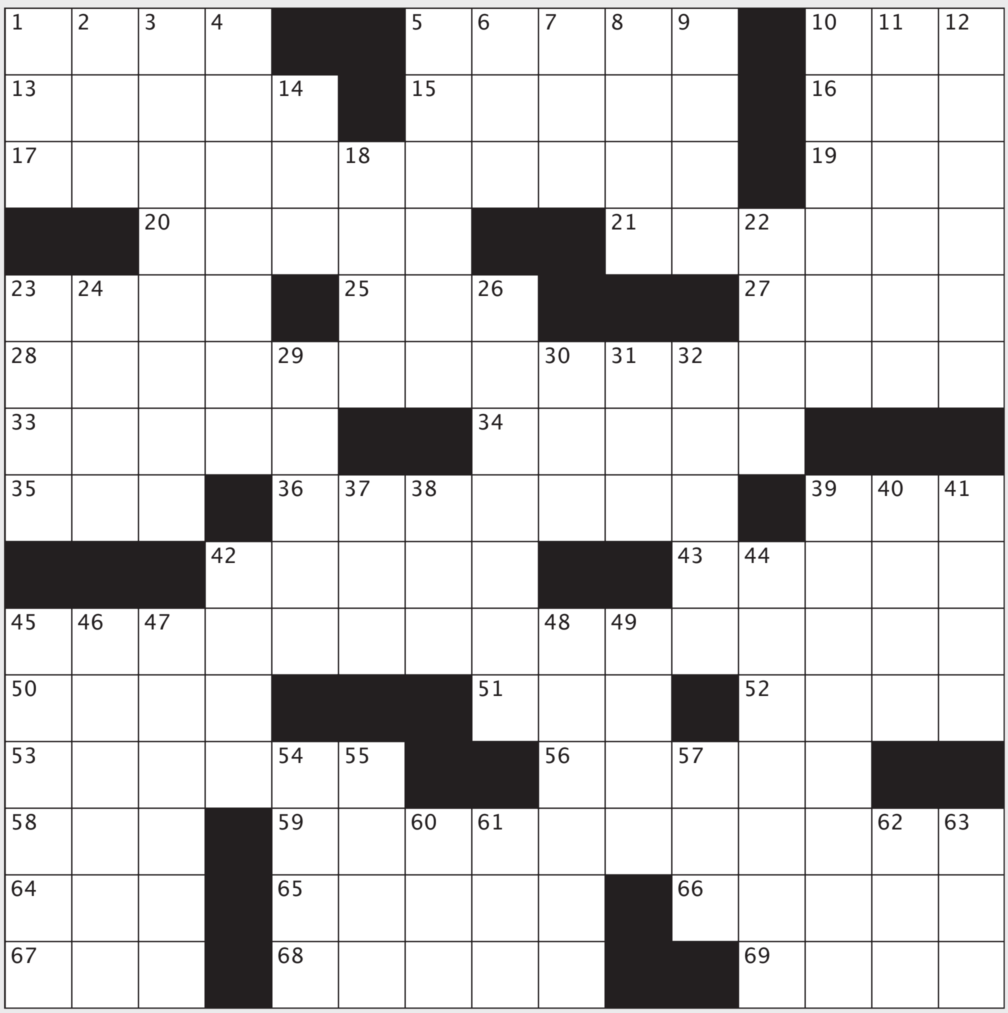
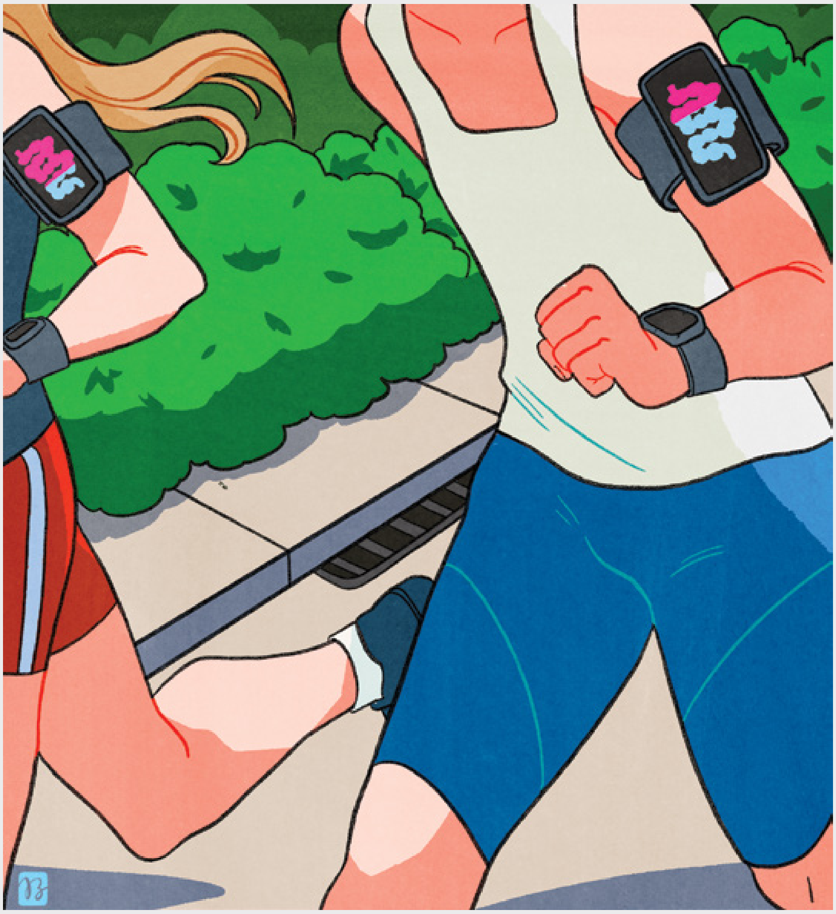
24 Gemstone in which a cicada was found preserved, pointing to new places to search for ancient life
26 Clique
29 Tennis star Agassi
30 Day- ___ paint
31 *Fear and Loathing in* ___ *Vegas*
32 Civilization whose math used hearts and arrows
37 Big part of an elephant
38 Knox and Bragg (abbr.)
39 X marks its spot
40 One of the Baldwin brothers
41 Unit of force
42 Assessment, informally
44 Puts the cuffs on
45 Cowboy seat
46 Like some T-shirt graphics
47 Fragrant blooms
48 Sartre play set in hell
49 It may get into a lather
54 Secondhand
55 Brownish purple
57 Distress signal
60 San Francisco's ___ Hill
61 Film director Roth
62 Feel sorrow over
63 Takeoff guess (abbr.)



For the solution, visit www.scientificamerican.com/games/science-crosswords



Exercise Improves Your Gut Microbe Health

A workout boosts your gut microbiome, and that helps the rest of you BY LYDIA DENWORTH

THE IDEA THAT OUR WORKOUTS could benefit the trillions of microbes that live in our guts—bacteria and viruses that help our immune systems, metabolism, digestion, and other key bodily functions—isn't obvious. At least it's not as obvious as the connection between diet and the gut microbiome, as these microbes are called. But evidence is growing that an aerobic workout such as jogging can improve the health of the gut microbes, which in turn improves overall physical health. There are early indications that the relationship works the other way, too: a healthy gut microbiome seems to increase exercise capacity.

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

"When people think about the gut, they default to diet and probiotics," says Sara Campbell, an exercise physiologist at Rutgers University who specializes in gut microbiota. But now many scientists are "moving toward the reality that exercise can be beneficial for the intestines," she says.

A "healthy" microbiome usually means gut bacteria are abundant and diverse; exercise appears to affect both these qualities. The gut microbes of an elite athlete are more diverse than those of nonathletes or recreational athletes. But a more pertinent issue for health, says Jacob Allen, an exercise physiologist at the University of Illinois Urbana-Champaign, is "what the microbe is actually doing."

One important finding is that aerobic exercise encourages activity in bacteria that produce short-chain fatty acids, which provide essential support for physiological processes. Most fatty acid molecules consist of 16 or 18 carbons, but—as the name suggests—short-chain fatty acids range from just one to six.

Of these smaller molecules, butyrate has emerged as an especially important link between exercise and the gut. It supplies energy for a variety of tissues, including the epithelial cells lining the gut, and it can reduce inflammation and improve the ability of cells to take in insulin. Our bodies naturally make a little bit of butyrate, but most is produced by microbes, and its output is boosted by aerobic exercise. (Very few studies have looked at the connection between strength training and butyrate levels, and those that have didn't find the same effect.)

This link between exercise and the gut was barely a glimmer in scientists' eyes some 15 years ago, when exercise immunologist Marc Cook was a graduate student at the Urbana-Champaign campus. He knew exercise improved symptoms of inflammatory bowel disease, particularly the type called ulcerative colitis. But scientists didn't understand why. Cook turned to mice to investigate and found that if they ran on a wheel, they were protected against a mouse version of colitis. In addition, there was a sevenfold increase in beneficial bacteria in the lining of the rodents' colons.

In a 2018 study, Allen, Cook (who is now at North Carolina A&T State University), and others tested a gut-health exercise intervention in humans for the first time. They trained both lean and obese people, all of whom were sedentary, to exercise on a treadmill or bike. Everyone started at moderate intensity three days a week and increased to one hour of high-intensity exercise per session.

After six weeks all participants showed increases in butyrate and two other short-chain fatty acids, acetate and propionate.

Illustration by Jay Bendt

They also got the expected benefits of exercise, such as reductions in fat mass and improvements in cardiorespiratory fitness. (All the effects were greater in lean people, a finding that the researchers don't yet understand.) After a further six weeks in which everyone stopped exercising, microbes in the gut returned to baseline levels, and health benefits decreased.

Researchers haven't fully teased out which effects of exercise can be directly attributed to microbiota versus the other changes brought on by physical activity, but there is a clear difference in gut environment. "We know there's a slight shunting of blood toward the muscles and away from the gastrointestinal tract during exercise," Allen says. That causes a small decrease in oxygen in gut tissue. There are changes in pH and temperature within the GI tract as well. Each of these shifts could affect which microbes survive.

Studies in humans are complicated by the enormous diversity of microbiomes from person to person and from group to group. Researchers are now trying to account for differences in response. Campbell is investigating variations by sex. Cook is studying the effects of short-chain-fatty-acid-producing bacteria in Black people, who have a high rate of hypertension. In a pilot study, he and his colleagues identified bacteria associated with high blood pressure in Black athletes, and they hope to identify a target for intervention.

As for the effects of microbiota on exercise capacity, most of that evidence comes from mice. Animals dosed with antibiotics to kill off their microbiomes exercise less than mice with healthy microbiomes and reach exhaustion faster. Research has also shown that an intact gut microbiota contributes to more muscle development.

This evolving research doesn't change the standard recommendation for human exercise, which is to engage in at least 150 minutes of moderate physical activity a week. But it adds strength to the arguments for doing such activity and may ultimately help explain why people respond to exercise differently. Someday there may even be a way boost the microbiome so that it responds better to time in the gym. Already, though, the science gives new meaning to the idea of gutting out your workout. ⬣

AN ELECTROLYSIS OF BRINE

$2NaCl(aq) + 2H_2O(l) \rightarrow H_2(g) + Cl_2(g) + 2NaOH(aq)$

I've rarely seen the sea so calm—
the weather almost balmy
as though the world knows
wind would blow me apart
tear the bonds already stretched
by atoms straining, seeking
the resistance of your arms
holding me together—
I tell you this—send it as text
across the waves
from Scotland to Norwegian coast
wondering if this is the one
that will weigh the radio waves
between us into wire
powered by the constant battery
of *good mornings* and *good nights*—
So that on days like this
when we both sit
dangling two feet into briny water
two million feet apart
we might become electrodes—
conductors in the beaker of the North Sea
attracting orchestras of ions
across aeons of ocean
until—
for one electrifying instant—
I feel the tingle of the touch
of electrons from the chlorine
in the salt of the sea that
kissed your feet
tightening me back into shape—
and I am Venus
born from the foam
of the telltale bubbles around me.

Alisz Reed is a writer and science communicator with a background in mathematics. She is currently working on a play about randomness while spending the year volunteering on a historic tall ship sailing around Scandinavia.

Illustration by Masha Foya

Talking about Race with Children

Children start learning about racism as early as preschool. Talking about it, however difficult, will help them become more antiracist BY SYLVIA PERRY

WHEN MY SON WAS THREE years old, he told me one day after preschool that he didn't want to play with me because I was Black. Black people are mean, he said, and he wanted to play only with his dad, who was white like him.

We were shocked, and I was hurt—my child thought I was bad because I was Black. And even though my son is biracial, he characterized himself as white.

What my son said that day unfortunately reinforced what research has long shown: children absorb racial biases from their environment. I study racial socialization—the ways children learn about race and racism—and I know how early these biases form. I also know that talking about race and racism can shape how children perceive others. Yet when white parents tell me their children say things like "Black people are not nice" or "I don't want to play with Black kids," they also tell me they ignore these statements or simply tell their children that such things are mean. Without a real conversation about why they might think this way or how to counter these ideas, children don't unlearn bias; they just learn not to say it out loud.

In 2022, even though research on white parents discussing racism was still emerging, my colleagues and I argued that they needed to have these conversations with their children. At the time, we pointed to the subtle things children can absorb racial biases from—the diversity (or lack thereof) of their parents' social circles, the characters they see on television and the differences they notice between social classes.

But in 2025 subtlety is a thing of the past. In attacking diversity, equity and inclusion initiatives, the Trump administration is legitimizing and emboldening racism in ways that children—especially white children—undoubtedly notice. If my son, at three years old, could absorb anti-Black messages when overt racism was more widely condemned, imagine what children today are internalizing in a climate where political leaders openly promote racism.

White parents who see themselves as egalitarian must recognize that the stakes are now higher than ever. If you want to raise children who reject racism rather than passively absorbing it, right now, today, talk with your child about race and racism.

By preschool, children start associating Black people with negative traits and white people with positive traits. These biases form as children pick up on patterns—who holds power, how groups are portrayed in media and how others interact with them. Even less obvious, nonverbal cues, such as someone smiling at one group and frowning at another, influence children's preferences. Not surprisingly, young children favor groups that receive positive signals and mimic those behaviors, reinforcing biases. These small cues accumulate, shaping how children perceive racial groups.

Most parents of color talk to their children early about race to prepare them for potential discrimination, but white parents often avoid these discussions. In our research on parents of children in the ranges of eight to 12 and 13 to 17 years of age, fewer than 40 percent of white parents talked to their children about race, and many who did downplayed racism. This avoidance is concerning, given how racial attitudes develop. Without parental guidance, children interpret racial patterns on their own, often reinforcing societal biases.

Sylvia Perry is an associate professor of psychology and an Institute for Policy Research Fellow at Northwestern University. She studies racial socialization and is a proud academic mama.

Our work revealed that some of the most common reasons white parents avoid discussing racism are the beliefs that their children are too young for such conversations and that they need to shield them from the reality of racism. This fear is unfounded. Studies show that, even in young children, when parents and teachers openly discuss race—explaining disparities and fairness—children develop less biased attitudes, greater empathy for people of color, and a stronger ability to recognize and challenge racism.

Talking about race and racism with children doesn't have to be overwhelming. As with many difficult topics, starting early and making these conversations a natural part of your family's dialogue can help children develop a more accurate and empathetic understanding of the world. Here's how:

- Start early with fairness and inclusion. Children understand and value fairness from an early age, and parents can use it as an entry point. When reading books or watching TV, ask: "Do you think it's fair if someone is treated differently just because of how they look?" Choose diverse books and media featuring characters of color as protagonists—not just in stories where they are struggling but as heroes and leaders.
- Use color-conscious language. Telling children "race doesn't matter" or "we're all the same" ignores the reality of racism. Instead explain that although everyone deserves equal treatment, some people face unfair challenges because of their race.
- Connect the past to the present: "A long time ago Black people weren't allowed to go to certain schools or have certain jobs. Although some things are better, Black people are still treated unfairly because of their race. Can you think of any examples?"
- Ask open-ended questions: "Have you ever seen someone treated unfairly because of their race? How did that make you feel?"
- Talk about stereotypes and bias.

Stereotypes are learned early, and children can recognize them if they are taught to think critically. When my son was five, we started talking about stereotypes—what they are and why they are unfair. A year later when we read “The Sneetches” by Dr. Seuss, a story in which Sneetches with stars on their bellies have negative assumptions about those without stars, he immediately made the connection. “Hey, that’s a stereotype!” he said. “There’s no reason to dislike them just because they don’t have stars.” He saw how stereotypes can lead to discrimination. These may seem like complex concepts, but children understand them when given the chance to do so.

- Talk about racism when it happens. If your child says something biased or asks a race-related question, that’s an opportunity for discussion. If they say something problematic, don’t shame them. Instead ask: “What made you think that?” Then gently correct misconceptions: “Actually that’s a stereotype, which means it’s an unfair way of thinking about a group of people.”

  If you witness racism together—on TV, in a book or in real life—use it as a teachable moment: “Why do you think that happened? How do you think that person felt?” This approach not only encourages empathy and perspective taking; it also equips children with the knowledge they need to understand what discrimination looks like and allows them to make sense of it should they witness it again.
- Create a supportive environment for questions. Children need to know that it’s okay to ask about race and racism. Foster an open, nonjudgmental space. If your child brings up race, don’t shut them down with “we don’t talk about that.” Instead say, “I’m really glad you asked. Let’s talk about it together.” Validate their feelings if they express confusion, sadness or anger about injustice.

After that unexpected and difficult conversation with my three-year-old, I began talking to him about race. At that age, he identified as white—not because we told him he was but because he was already learning that white was seen as the “better” color to be. But through our ongoing conversations, his understanding has evolved.

At first we talked about skin tone—how people come in different shades and how all skin tones are beautiful. Over time these discussions grew to include fairness, history and the experiences of Black people. Now he’s seven. When writing this article, I asked him how he identifies. He said, “I identify as a mixed person who is a descendant of African people who were enslaved.” But he also recognizes that he has grandparents who came from Poland, Italy, Ireland and England.

These conversations aren’t always easy. Sometimes learning about the difficult parts of Black history makes my son sad. But he also feels proud—proud to be part of a lineage of people who fought for justice and equal rights. And as he continues to navigate what it means to be multiracial in America, we talk about the complexities of being both Black and white. His understanding of race is still forming, and at times he feels conflicted. But what matters most is that he knows that he can ask questions and share his feelings and that these conversations will always be open. I feel lucky that he shared his thoughts with me that day and even luckier that he knows he can always come to me with questions about race and racism.

Talking about race and racism doesn’t make a child racist. Raising an antiracist child isn’t about checking a box or making a onetime statement. It is an ongoing process that requires honest, intentional conversations. If we want the next generation to be less racist than the ones that came before, the time to start is now. ●

For the most current, rigorous evidence to help you make the best decisions, go to **www.ScientificAmerican.com/column/the-science-of-parenting**

Illustration by Malte Müller

What Would Aliens See?

Can extraterrestrials detect our civilization from a distance? BY PHIL PLAIT

SO FAR ASTRONOMERS have discovered nearly 6,000 exoplanets—worlds that orbit stars other than our sun. If that number already feels ridiculously large, you'd better brace yourself: extrapolation of that total suggests there could be hundreds of billions of planets in our galaxy alone. Some fraction of them will be like Earth, although at the moment we don't know what that fraction is. Still, with an amount that huge, even a small percentage of Earth-like orbs could mean a lot of habitable planets.

That's why most scientists take the idea of life on other worlds seriously. Life arose here pretty rapidly—practically as soon as Earth had cooled enough to harbor oceans—which implies that it's easy to get started once conditions are clement. The timing of the advent of hazily defined, higher-order features such as intelligence and technology, however, is a different question and one about which we are mostly restricted to speculation (although there have been some interesting investigations). But let's say that right now there are intelligent aliens and technological civilizations out there somewhere in the Milky Way. Could they detect us?

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

With the question phrased that way, in the most general sense the answer is yes. By this I mean there's no physical reason you couldn't build an immense telescope, one far, far larger than any currently in existence, that would be capable of taking a detailed image of a planet from a great many light-years away. The engineering task may be considerable, but it's not technically impossible. Then it might only be a matter of seeing city lights at night, for example, to confirm that aliens—that is, humans, because we'd be alien to them—exist.

In fact, it may be even easier than that. A much smaller telescope need not resolve the planet; just observing it well enough to watch it get brighter and dimmer as nighttime cities rotate into and out of view might be good enough. And that "smaller" telescope would have to be, oh, let's say, only ridiculously huge instead of overwhelmingly so.

The reason to wonder about any of this is that it flips the script on what's usually asked, which is how we can detect aliens given our current level of technology. We can't know their level in advance, but we do know our own—so it makes sense to assume their tech is equivalent to ours and then ask from what distance they could spot us.

That task is actually extremely difficult. Space is big, and vast distances dim even the mightiest of civilizations. But we can use our own as a template and work backward to estimate the outer limits of any interstellar eavesdropping on our noisy little world by extraterrestrials that use similar technology.

A team of astronomers headed by Sofia Sheikh of the SETI Institute has run the numbers on this question and published its results in the *Astronomical Journal*. ("SETI" stands for "search for extraterrestrial intelligence.") The researchers looked at various methods of detecting our various so-called technosignatures and found that the answer, unsurprisingly, depends on which specific one any extraterrestrials would be looking for. Many such ideas have been investigated individually before, but this recent analysis examines them collectively and consistently to arrive at some fresh insights.

Illustration by Scott Brundage

One example of a technosignature is radio. Since its inception in the mid-20th century, SETI has focused on detecting artificial radio signals from space. Radio waves are easy to make and detect, and they can pass at the speed of light through interstellar space, scarcely impeded by any gas or dust that might be in the way. That makes radio a nearly ideal carrier for galactic-range communication.

The astronomers divided radio signals into four categories: first, pointed but intermittent broadcasts to space, essentially "we are here" messages; second, intentional and persistent targeted signals sent to our planetary probes in deep space that continue on into the galaxy; third, persistent omnidirectional signals, such as "leakage" emissions from cell-phone towers, as well as radio and television stations; and fourth, signals from artifacts, such as low-power downlinks from our interplanetary probes.

Signals in the first category can be detected from the farthest away because the power involved in their transmission is highest. Sheikh and her colleagues estimate that these waves can be spotted at a staggering 12,000 light-years from Earth! That's a maximum distance, but several billon stars lie within that range. If you want to be found, this is probably the way to go.

The other methods don't fare as well. For the second category, the maximum distance is more like 65 light-years, which still includes thousands of stars. The third category gets out to only four light-years, which isn't even as far as the closest star to the sun. (That star, Proxima Centauri, is 4.25 light-years away.) The fourth one, which would include signals from our spacecraft, such as the Voyager 1 probe, has a detection limit of just under one light-year away. That surprised me, given how weak the signal is now, when the spacecraft is "only" about 25 billion kilometers away. Voyager 1's 23-watt transmitter is already dimmed to less than a billionth of a billionth of a watt as seen from our world.

Clearly, radio is the method of choice for aliens looking for Earth. But there are other signatures.

Altering our planet's climate is not great, to say the least, but it does make a signature detectable from space.

One outcome of our modern civilization is an imprint on our atmosphere. Besides carbon dioxide, quite a few other chemicals have been dumped into our air by industry and other anthropogenic sources. Altering our planet's climate is not great, to say the least, but it does make a signature detectable from space. And that signature could be especially obvious for interstellar observers located along our solar system's ecliptic, the plane of Earth's orbit around the sun. From that perspective, they would see our planet pass directly in front of our star once every year, slightly dimming its light. Called a transit, this has been the most successful method so far for discovering exoplanets.

Such transits can also be used to remotely analyze a world's air. As starlight (or, in our case, sunlight) passes through a planet's upper atmosphere, certain wavelengths of light will be absorbed by molecules there, creating a kind of fingerprint that can be measured. We already use this method to study some transiting exoplanets with the James Webb Space Telescope (JWST). And proposed future telescopes such as NASA's Habitable Worlds Observatory are meant to scan the atmospheres of dozens of potentially Earth-like exoplanets that may exist around nearby stars (even if they don't transit as seen from our solar system).

In their study, the SETI Institute astronomers focused on the remote detection of nitrogen dioxide, or NO_2, a conspicuous by-product of fossil-fuel burning. Given the current levels in our polluted air, they find that we could detect such a signature from a distance of 5.7 light-years. Only the Alpha Centauri system is within that range, which limits any aliens' options for uncovering us. Still, it's an impressive technological achievement to be able to do this kind of search at all.

Most other types of technosignatures aren't as helpful. A JWST clone perched somewhere in the vicinity of Neptune's orbit could detect the infrared glow of heat emanating from our cities, but farther out that trail grows cold. At about 100 times that distance, the optical gleam of Earth's city lights would fade to black—better but still far short of even our next-nearest star.

Lasers are easier to detect and are already being tested by NASA and the European Space Agency for in-space satellite communication. Still, under reasonable assumptions, a laser's beam of focused light would be too dim to detect from a distance of just under six light-years, which is not enough to be spotted even at Barnard's star, the second-closest star system to our own.

The worst case involves searches for our off-world technological artifacts. Earth's swarms of artificial satellites, for example, slightly change the amount of sunlight our planet blocks during a transit but not enough to be detectable even from Mars. Suffice to say that if aliens were close enough to see such things, there would be far easier ways for them to spot us.

All these numbers come with the pretty big caveat that the extraterrestrials are no more advanced technologically than we are. This assumption may be very conservative because, after all, we get more advanced all the time. We continue to build bigger telescopes, limited only by budget and the laws of physics, and we are still finding and developing new ways to investigate the cosmos, such as detecting neutrinos and gravitational waves. We've been doing what might be called "modern" astronomy for only a century or so, and it's difficult to predict where we might be 100 years hence.

The galaxy has been around for billions of years. No one can say yet who else shares it with us or what they're using to explore it. The truth is out there, and turning our search for aliens inside out—by looking from the outside in—may best inform us on how to find it. ⬣

Stormy Waters

Deadly storm surges may become more common and severe

TEXT BY CLARA MOSKOWITZ | GRAPHICS BY JEN CHRISTIANSEN | MAPS BY DANIEL P. HUFFMAN

THE BEGINNING OF JUNE marks the start of the Atlantic hurricane season, the six-month period when strong storms can brew in the ocean and then wreak havoc on land. Among the hazardous consequences of hurricanes are storm surges, in which water rapidly rises above the normal tide level on shore. These dangerous events can cause flooding and pick up and displace homes and other structures. "Water is very powerful," says Heather Nepaul, a meteorologist at the National Oceanic and Atmospheric Administration's National Hurricane Center in Miami. "It can be a deadly situation."

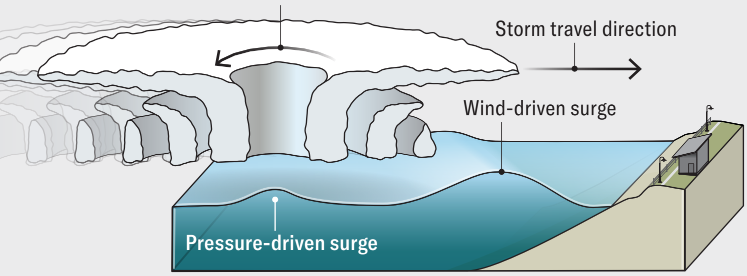
Surges occur when the strong winds of a hurricane interact with ocean waters, piling up water ahead of the storm. As the hurricane heads toward shore, it travels over shallower ocean, and the water it carries has nowhere to go but upward onto land.

How severe a surge will be depends on many factors, including the characteristics of the coastline and the intensity, size and angle of approach of the storm. In general, though not always, stronger and larger storms produce higher storm surges.

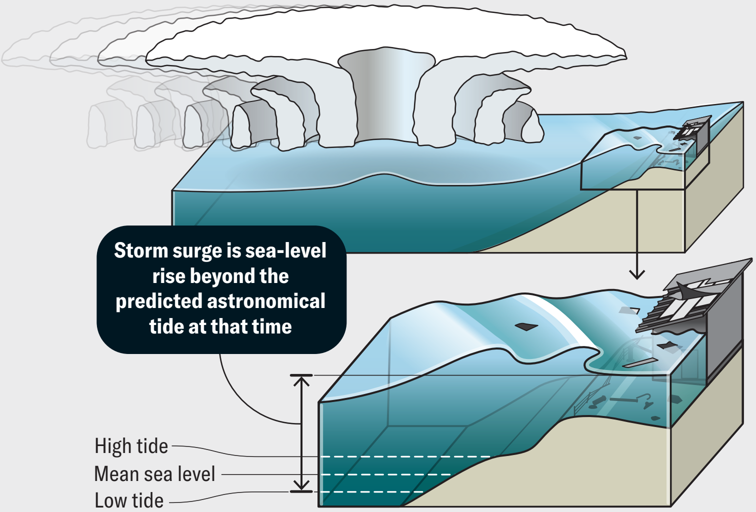
As the climate warms, hurricanes are becoming more intense, and sea levels are rising. Both of these effects are likely to worsen storm surges. Coastal areas that are already vulnerable to storm surge could experience worse impacts, and places that aren't quite vulnerable now may become increasingly at risk.

HOW IT WORKS

The bulk of a storm surge is caused by wind pushing water ashore. A small part of the effect, however, results from the low atmospheric pressure inside a storm, which decreases the amount of downward force on the ocean, triggering a rise in water level.



As the storm advances, its spiral of air pulls ocean water up into its center. When it nears land, the excess water surges over the shore above and beyond the normal tide level.



VARIABLES THAT AFFECT STORM SURGE HEIGHT

The severity of storm surges is hard to predict because it depends on so many variables: the speed and radius of the wind associated with the storm, the hurricane's size, the speed and angle at which the storm approaches land, and the specific shape of the shoreline where it hits.

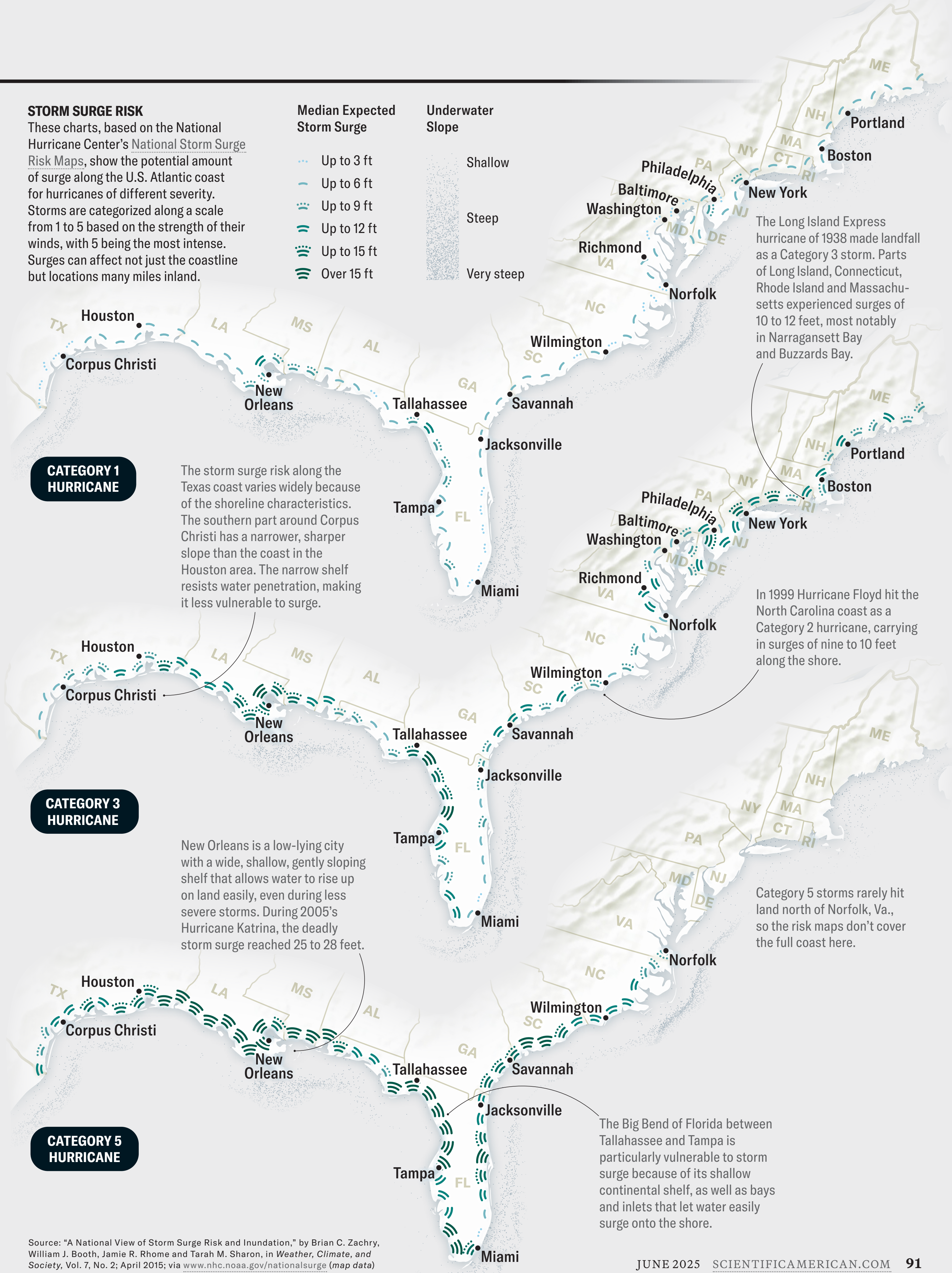
	STORM SURGE HEIGHT: LOWER	STORM SURGE HEIGHT: HIGHER
Wind speed	Slower	Faster
Wind radius	Smaller	Larger
Shape of the shoreline	Steeply sloping narrow shelf	Gently sloping wide shelf

Speed of storm travel
Faster-moving storms tend to produce higher maximum surge levels along the immediate coast. Slower storms may result in lower surge heights along the coast, but the water can penetrate much farther inland.

Angle of approach
A storm that hits the coast straight-on will often result in a higher surge height than a storm with an oblique approach. But this can be tricky to generalize because it also depends on the coastline's complexity. For example, a storm moving parallel to the coast can still push water into bays, resulting in significant surge.

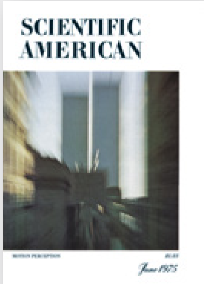
STORM SURGE RISK

These charts, based on the National Hurricane Center's National Storm Surge Risk Maps, show the potential amount of surge along the U.S. Atlantic coast for hurricanes of different severity. Storms are categorized along a scale from 1 to 5 based on the strength of their winds, with 5 being the most intense. Surges can affect not just the coastline but locations many miles inland.



Source: "A National View of Storm Surge Risk and Inundation," by Brian C. Zachry, William J. Booth, Jamie R. Rhome and Tarah M. Sharon, in *Weather, Climate, and Society*, Vol. 7, No. 2; April 2015; via www.nhc.noaa.gov/nationalsurge (*map data*)

50, 100 & 150 Years



SLAVERY BY ANTS IS SELF-DESTRUCTIVE

1975 "The institution of slavery is not unique to human societies. No fewer than 35 species of ants depend to some extent on slave labor for their existence. The techniques by which they raid other ant colonies to strengthen their labor force rank among the most sophisticated behavior patterns found in the insect world. Most of the slave-making species are so specialized as raiders that they starve to death if deprived of their slaves. Together they display an evolutionary descent that begins with casual raiding by otherwise free-living colonies, passes through the development of full-blown warrior societies and ends with such degeneration that the workers can no longer even conduct raids. —*Edward O. Wilson"*

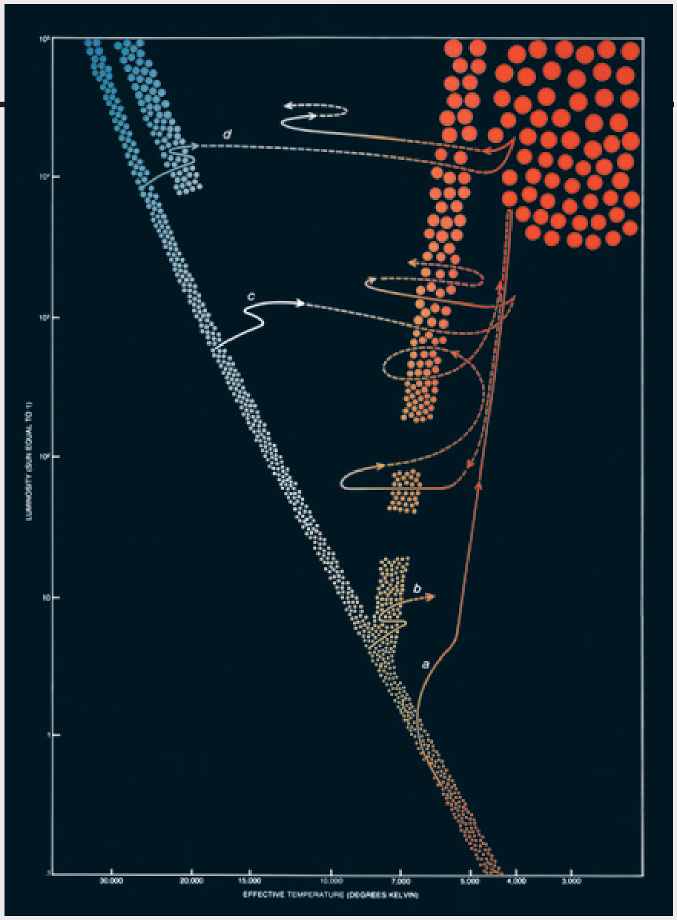
TORNADO OUTBREAK LARGEST ON RECORD

"During the spring and early summer tornadoes are likely to occur between the Gulf of Mexico and Lake Ontario. On April 3 of last year conditions were right. The first tornado struck at 1:10 P.M. By 5:20 A.M. the next day a total of 148 tornadoes had swept across the countryside and cities from Laurel, Miss., to Windsor, Ont., killing 315 people and injuring 5,484. In terms of sheer scope and the number of storms, it was the largest tornado outbreak on record. Immediately after, Theodore Fujita of the University of Chicago and his colleagues organized aerial and ground surveys. Fujita and his co-workers found that 74 percent of the fatalities occurred in houses and buildings, 17 percent in mobile homes, 6 percent in automobiles and 3 percent among people en route to shelter."

In 1971 Theodore Fujita and Allen Pearson introduced the Fujita-Pearson scale to describe tornado intensity, from 0 (wind speed less than 73 mph) to 5 (261 to 318 mph).

VACATION FUN WITH MUD DWELLERS

1925 "The trouble with vacations is that they have a way of being just what their name implies: too vacant. Few human experiences are worse than that of the individual who finds themself sitting around in the country or at the seashore with 24 hours a day on their hands and nothing interesting to do. Science can help. Anywhere in the out of doors there is opportunity for real fun with science. In this issue, we describe some of the interesting things you can do and see with rocks and streams and the sides of hills. And we explain some secrets of the clouds. Another good way to make your vacation interesting is to study mud. In the bottoms of sluggish streams and small fresh-water ponds, even water-filled ditches along the roadside, there is a vast and interesting world of tiny creatures. Science calls them animalcules, protozoa, protophyta, and other long names. You cannot see them without a microscope. But for the price of one weekend visit to a moderately fashionable resort you can buy a microscope. You can take it out anywhere and discover this intensely interesting world of the mud dwellers."



1975, Star Chart: "In the Hertzsprung-Russell diagram, the dot colors and sizes represent the apparent colors and approximate relative sizes of the stars. The majority of normal stars lie on or near the main sequence, from the upper left to lower right. The more massive the star, the higher on the sequence. Pulsating stars are distributed quite differently, from the upper right down toward the main sequence. Stars reach instability regions by proceeding along evolutionary tracks (*arrows*) across their lifetime."

Scientific American, Vol. 232, No. 6; June 1975

WHITE ANTS DESTROY SAINT HELENA

1875 "White ants were introduced into Saint Helena island [in the South Atlantic Ocean] in 1840 in some timber from a slave ship. Mr. M'Lachlan has identified the species *termes tenuis,* peculiar to South America. The mischief it has done is almost incredible, and it appears to have gradually destroyed the whole of Jamestown. A considerable portion of the books in the public library, especially theological literature, was devoured by them, and the whole of the interior would be destroyed without the exterior of the volumes seeming otherwise than intact."

The insects are known today as Heterotermes tenuis, *a subterranean termite.*

COOKING WITH GAS

"A gas-burning cooking stove has been invented by B. Giles of Blackheath, England. He claims to have succeeded in cooking the most delicate dishes without their imbibing the slightest flavor from the products of combustion."

THE GREATEST CHALLENGES OF OUR TIME

THROUGH THE EYES OF THE GLOBAL HERO WHO CHANGED THE COURSE OF HISTORY

HISTORIC EVENT

AN EVENING WITH PRESIDENT

LECH WALESA

NOBEL PEACE PRIZE WINNER AND FORMER PRESIDENT OF POLAND

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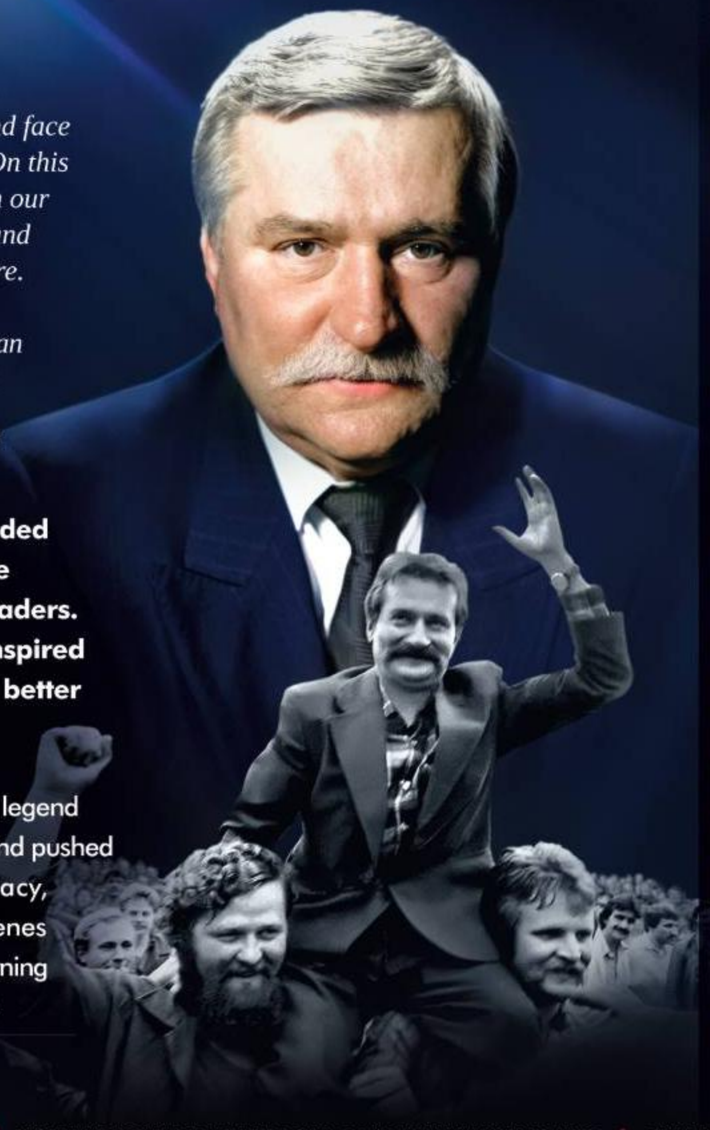
— **Lech Walesa**



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Sep 20	Dallas, TX
Sep 22	Atlanta, GA
Sep 24	Columbus, OH
Sep 26	Pittsburgh, PA
Sep 27	Baltimore, MD
Sep 28	Cleveland, OH
Sep 30	Minneapolis, MN
Oct 2	St. Louis, MO
Oct 4	Chicago, IL
Oct 5	Milwaukee, WI
Oct 9	Miami, FL
Oct 11	Orlando, FL
Oct 13	Boston, MA
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SCIENTIFIC AMERICAN, JUNE 2025: PAGE 35

"COSMIC DAWN," by Rebecca Boyle, should have said that sometime between 50 million and 100 million years after the big bang, gravity drew hydrogen atoms together and ignited the first stars.

SCIENTIFIC AMERICAN, JUNE 2025: PAGE 43

"REFREEZING THE ARCTIC," by Alec Luhn, said that the Bright Ice Initiative had scattered tiny glass beads on glaciers in Iceland and India to reflect sunlight. The organization initially used that approach in a field test in Iceland. It subsequently switched to a clay-based material, which it used in a field test in the Himalayas.