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Cosmic Voids

Huge empty patches could help solve the universe's greatest mysteries

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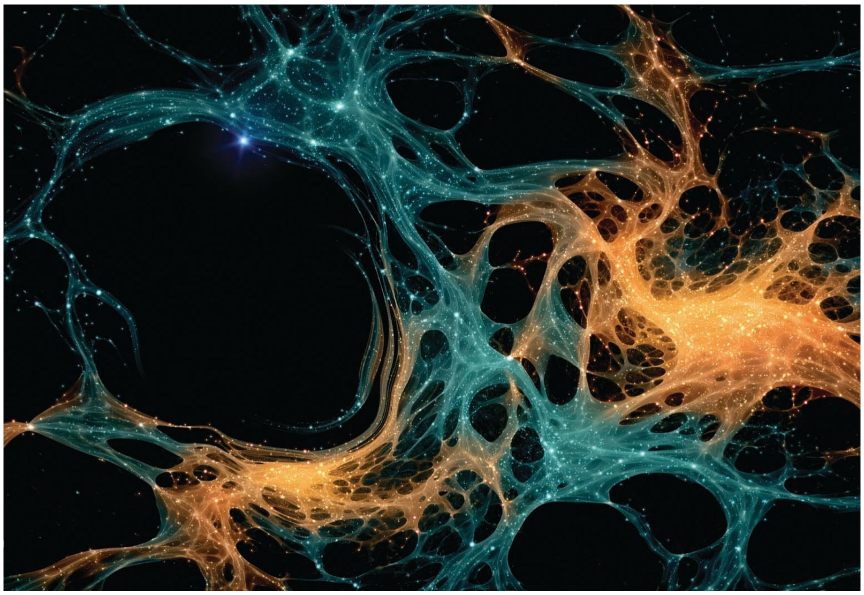
How Analyzing Cosmic Nothing Might Explain Everything

Huge empty areas of the universe called voids could help solve the greatest mysteries in the cosmos

By Michael D. Lemonick



Chris Wren and Kenn Brown/mondoworks

Computational astrophysicist Alice Pisani put on a virtual-reality headset and stared out into the void—or rather *a* void, one of many large, empty spaces that pepper the cosmos. “It was absolutely amazing,” Pisani recalls. At first, hovering in the air in front of her was a jumble of shining dots, each representing a galaxy. When Pisani walked into the jumble, she found herself inside a large swath of nothing with a shell of galaxies surrounding it. The image wasn’t just a guess at what a cosmic void might look like; it was Pisani’s own data made manifest. “I was completely surprised,” she says. “It was just so cool.”

The visualization, made in 2022, was a special project by Bonny Yue Wang, then a computer science undergraduate at the Cooper

Union for the Advancement of Science and Art in New York City. Pisani teaches a course there in cosmology—the structure and evolution of the universe. Wang had been aiming to use Pisani's data on voids, which can stretch from tens to hundreds of millions of light-years across, to create an augmented-reality view of these surprising features of the cosmos.

The project would have been impossible a decade ago, when Pisani was starting out in the field. Scientists have known since the 1980s that these fields of nothing exist, but inadequate observational data and insufficient computing power kept them from being the focus of serious research. Lately, though, the field has made tremendous progress, and Pisani has been helping to bring it into the scientific mainstream. Within just a few years, she and an increasing number of scientists are convinced, the study of the universe's empty spaces could offer important clues to help solve the mysteries of dark matter, dark energy and the nature of the enigmatic subatomic particles called neutrinos. Voids have even shown that Einstein's general theory of relativity probably operates the same way at very large scales as it does locally—something that has never been confirmed. "Now is the right moment to use voids" for cosmology, says David Spergel, former chair of astrophysics at Princeton University and current president of the Simons Foundation. Benjamin Wandelt of the Lagrange Institute in Paris echoes the sentiment: "Voids have really taken off. They're becoming kind of a hot topic."

The discovery of cosmic voids in the late 1970s to mid-1980s came as something of a shock to astronomers, who were startled to learn that the universe didn't look the way they'd always thought. They knew that stars were gathered into galaxies and that galaxies often clumped together into clusters of dozens or even hundreds. But if you zoomed out far enough, they figured, this clumpiness would even out: at the largest scales the cosmos would look homogeneous. It wasn't just an assumption. The so-called cosmic microwave background (CMB)—electromagnetic radiation emitted about 380,000 years after the big bang—is extremely homogeneous, reflecting smoothness in the distribution of matter when it was created. And even though that was nearly 14 billion years ago, the modern universe should presumably reflect that structure.

But we can't tell whether that's the case just by looking up. The night sky appears two-dimensional even through a telescope. To confirm the presumption of homogeneity, astronomers needed to know not only how galaxies are distributed across the sky but how they're distributed in the third dimension of space—depth. So they needed to measure the distance from Earth to many galaxies near and far to figure out what's in the foreground, what's in the background and what's in the middle. In 1978 Laird A. Thompson of the University of Illinois Urbana-Champaign and Stephen A. Gregory of the University of New Mexico did just that and discovered the first hints of cosmic voids, shaking the presumption that the universe was smooth. In 1981 Harvard University's Robert Kirshner and four of his colleagues discovered a huge void, about 400 million light-years across, in the direction of the constellation Boötes. It was so big and so empty that "if the Milky Way had been in the center of the Boötes void, we wouldn't have known there were other galaxies [in the universe] until the 1960s," as Gregory Scott Aldering, now at Lawrence Berkeley National Laboratory, once put it.

In 1986 Margaret J. Geller, John Huchra and Valérie de Lapparent, all then at Harvard, confirmed that the voids Thompson, Kirshner and their colleagues had found were no flukes. The team had painstakingly surveyed the distance to many hundreds of galaxies spread out over a wide swath of sky and found that voids appeared to be everywhere. “It was so exciting,” says de Lapparent, now a senior researcher at the Institut d’Astrophysique de Paris (IAP). She had been a graduate student at the time and was spending a year working with Geller, who was trying to understand the large-scale structure of the universe. A cross section of the local cosmos that astronomers had put together earlier showed hints of a filamentary structure consisting of regions either overdense or underdense with galaxies. “Margaret had this impression that this was just an observing bias,” de Lapparent says, “but we had to check. We wanted to look farther out.” They used a relatively small telescope on Mount Hopkins in Arizona. “I learned to observe on that telescope,” de Lapparent recalls. “I was on my own after a night of training, which was so exciting.” When she was done, she, Geller and Huchra made a map of the galaxies’ locations. “It was amazing,” she says. “We had these big, circular voids and these sharp walls full of galaxies.”

“All of these features,” the researchers wrote in their paper, entitled “A Slice of the Universe,” “pose serious challenges for current models for the formation of large-scale structure.” As later, deeper surveys would confirm, galaxies and clusters of galaxies are themselves concentrated into a gigantic web of concentrated regions of matter connected by streaming filaments, with gargantuan voids in between. In other words, the cosmos today vaguely resembles Swiss cheese, whereas the CMB looks more like cream cheese.

The question, then, was: What forces made the universe evolve from cream cheese into Swiss cheese? One factor was almost certainly dark matter, the invisible mass whose existence had in the 1980s only recently been accepted by most astrophysicists, despite years of tantalizing evidence from observers such as Vera Rubin and Fritz Zwicky. It was more massive than ordinary, visible matter by a factor of six or so. That would have made the gravitational pull of slightly overdense regions in the early universe stronger than anyone had guessed. Stars and galaxies would have formed preferentially in these areas of high density, leaving low-density regions largely empty.

> The study of the universe’s empty spaces could offer important clues to help solve the mysteries of dark matter, dark energy and the nature of neutrino particles.

Most observers and theorists continued to explore what would come to be known as the “cosmic web,” but very few concentrated on voids. It wasn’t for lack of interest; the problem was that there wasn’t much to look at. Voids were important not because of what they contained but because their very existence, their shapes and sizes and distances from one another, had to be the result of the same forces that gave structure to the universe. To use voids to understand how those forces worked, astrophysicists needed to include many examples in statistical analyses of voids’ average size and shape and separation, yet too few had been found to draw useful conclusions from them. It was analogous to the situation with exoplanets in the 1990s: the first few discovered were proof that planets did indeed orbit stars beyond the sun, but it wasn’t until the Kepler space telescope began raking them in by the thousands after its 2009 launch that planetary scientists could say anything meaningful about how many and what kinds of planets populated the Milky Way.

Another issue with studying voids was raised in 1995 by Barbara Ryden of the Ohio State University and Adrian L. Melott of the University of Kansas. Galaxy surveys, they pointed out, are conducted in “redshift space,” not actual space. To understand what they meant, consider that as the universe expands, light waves are stretched from their original wavelengths and colors into longer, redder wavelengths. The farther away something is from an observer, the more its light is stretched. The James Webb Space Telescope was designed to be sensitive to infrared light in part so it can see the very earliest galaxies, whose light has been stretched all the way out of the visible spectrum—it's redder than red. And the CMB, the most distant light we can detect, has been stretched so much that we now perceive it in the form of microwaves.

"Measuring the physical distances to galaxies is difficult," Ryden and Melott wrote in a paper in the *Astrophysical Journal*. "It's much easier to measure redshifts." But, they noted, redshifts can distort the actual distances to galaxies that enclose a void and thus give a misleading idea of their size and shape. The problem, explains Nico Hamaus of the Ludwig Maximilian University of Munich, is that as a void expands, "the near side is coming toward us, and the far side is streaming away." That differential subtracts from the redshift on the near side and adds to it on the far side, making the void look artificially elongated.

A Map of Nothing

Regions of relatively empty space called cosmic voids are everywhere in the universe, and scientists believe studying their size, shape and spread across the cosmos could help them understand dark matter, dark energy and other big mysteries. To use voids in this way, astronomers must map these regions in detail—a project that is just beginning. Shown here are voids discovered by the Sloan Digital Sky Survey (SDSS), along with a selection of 16 previously named voids. Scientists expect voids to be evenly distributed throughout space—the lack of voids in some regions on the globe simply reflects SDSS's sky coverage.

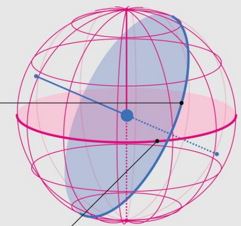
The sphere below holds 6,448 voids, mapped in space using the galactic coordinate system. Every void is repeated at a smaller size on the Milky Way's so-called galactic plane (*central slice*) for a clearer look at its light-travel distance to Earth. (The time light took to travel to us from that point is represented in gigayears, or Gyr.) Familiar benchmarks—in the form of stars and constellations—are projected onto the sphere at 7 Gyr from Earth, as all of the shown voids are found within this radius.

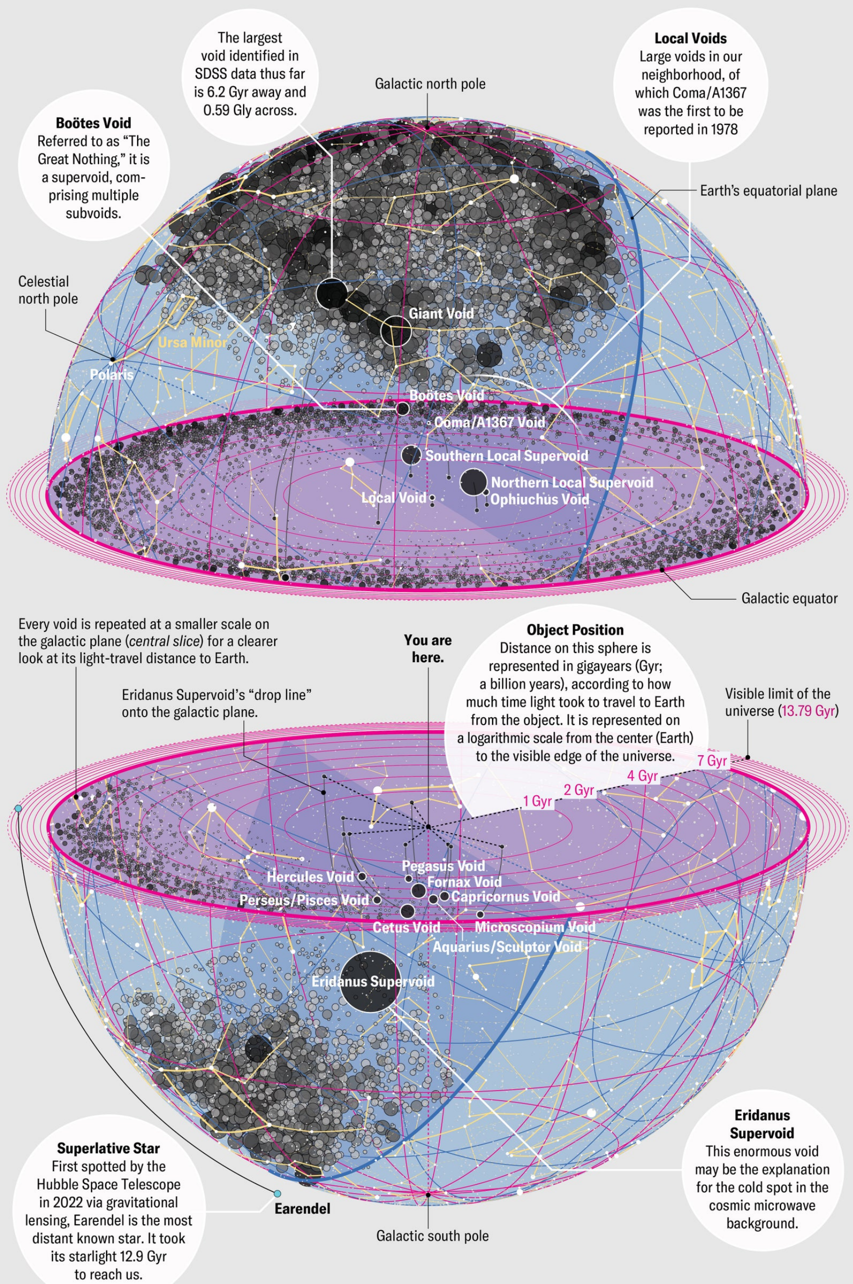
ESTIMATED VOID SIZE
Gigalight-years (Gly, billions of light-years)
0.1 0.2 0.3 0.4 0.5

STAR MAGNITUDE
(Apparent brightness from Earth)
Brightest ←
0 1 2 3 4 5 6 7 8

The equatorial coordinate system is oriented relative to the equator of Earth and measures positions of objects in the sky using right ascension (0–24 h) and declination (–90° to 90°).

The galactic coordinate system is oriented relative to the plane of the Milky Way and measures positions of objects in the sky using longitude (0–360°) and latitude (–90° to 90°).





Martin Krzywinski; Sources: Sofia Contarini/University of Bologna, Nico Hamaus/Ludwig Maximilian University of Munich and Alice Pisani/Cooper Union, CCA Flatiron Institute, Princeton University; "Cosmological Constraints from the BOSS DR12 Void Size Function," by Sofia

Contarini et al., in *Astrophysical Journal,* Vol. 953; August 2023; "Precision Cosmology with Voids in the Final BOSS Data," by Nico Hamaus et al., *in Journal of Cosmology and Astroparticle Physics,* No. 12; December 2020 (*void data*)

Despite the difficulties, astrophysicists began to feel more equipped to tackle voids by the late 2000s. Projects such as the Sloan Digital Sky Survey had probed much more deeply into the cosmos than the map made by Geller, Huchra and de Lapparent and confirmed that voids were everywhere you looked. Independent observations by two teams of astrophysicists, meanwhile, had revealed the existence of dark energy, a kind of negative gravity that was forcing the universe to expand faster and faster rather than slowing down from the mutual gravitational attraction of trillions of galaxies. Voids seemed to offer astronomers a promising way of studying what might be driving dark energy.

These developments caught Wandelt's eye. His specialty has always been trying to understand how the large-scale structure of the modern universe came to be. One of the aspects of voids that he found attractive, he says, was that "these underdense regions are much quieter in some ways, more amenable to modeling" than the clusters and filaments that separate them. Galaxies and gases are crashing into each other in nonlinear and complicated interactions, Wandelt says. There's "a chaos" that erases the information about their formation. Further complicating things, the gravitational attraction between galaxies is strong enough on smaller scales that it counteracts the general expansion of the universe—and even counteracts the extra oomph of dark energy. Andromeda, for example, the nearest large galaxy to our own, is actually drawing closer to the Milky Way; in four billion years or so, they'll merge. Voids, in contrast, "are dominated by dark energy," Wandelt says. "The biggest ones are actually expanding faster than the rest of the universe." That makes them ideal laboratories for getting a handle on this still puzzling force.

And it's not just an understanding of dark energy that could emerge from this line of study; voids could also cast light (so to speak) on the nature of dark matter. Although voids have much less dark matter in them than the clusters and filaments of the cosmic web do, there’s still some. And unlike the chaotic web, with its swirling hot gases and colliding galaxies, the voids are calm enough that the particles astrophysicists think make up dark matter might be detectable. They wouldn’t show up directly, because they neither absorb nor emit light. But the particles should occasionally collide, resulting in tiny bursts of gamma rays. They would also probably decay eventually, releasing gamma rays in that process as well. A sufficiently sensitive gamma-ray telescope in space would theoretically be able to detect their collective signal. Nicolao Fornengo of the University of Turin in Italy, co-author of a study laying out this rationale, has said that “if dark matter produces [gamma rays], the signal should be in there.”

The Vera C. Rubin Observatory on the Cerro Pachón mountain in Chile will make detailed night-sky surveys that reveal new voids in unprecedented detail.
NOIRLab/NSF/AURA

Voids could even help to nail down the nature of neutrinos—elementary particles, once thought to be massless, that pervade the universe while barely interacting with ordinary matter. (If you sent a beam of neutrinos through a slab of lead one light-year, or nearly six trillion miles, thick, about half of them would sail through it effortlessly.) Physicists have confirmed that the three known types of neutrinos do have masses, but they aren't sure why or exactly what those masses are.

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Voids could help them find the answer, says Elena Massara, a data scientist at the University of Waterloo in Canada and former postdoctoral researcher at the Waterloo Center for Astrophysics. They’re places that have a lack of both luminous matter and dark matter, she explains, “but they’re full of neutrinos, which are almost uniformly distributed” through the universe, including in voids. That’s because neutrinos zip through the cosmos at nearly the speed of light, which means they don’t clump together under their mutual gravity—or under the gravity of the dark matter concentrations that act as the scaffolding for the cosmic web. Although voids always contain a lot of neutrinos, the particles are only passing through—those that fly out are constantly replenished by more neutrinos streaming in. And their combined gravity can make the voids grow more slowly over time than they would otherwise. The rate of growth—determined through comparison of the average size of voids in the early universe to those in the modern universe—can reveal how much mass neutrinos actually have.

Void science has changed a lot since Pisani started studying it as a graduate student working with Wandelt. He offered two or three suggestions for a dissertation topic, she recalls, and one of them was cosmic voids. “I felt that they were the riskiest choice,” she says, “because there were very few data at the time. But they were also incredibly challenging," which she found exciting. The data Pisani and others needed to analyze the voids, however—that is, to test their real-world properties against computer models incorporating dark matter, dark energy, neutrinos and the formation of large-scale structure in the universe—were simply not available. "When I started my Ph.D. thesis," Pisani says, "we knew of fewer than 300 voids, something like that. Today we have on the order of 6,000 or more."

That's huge, but it's still not enough for the comprehensive statistical analysis necessary for voids to be used for serious cosmology—with one exception. In 2020 Hamaus, Pisani, Wandelt and several of their colleagues published an analysis showing that general relativity behaves at least approximately the same way on very large scales as it seems to do in the local universe. Voids can be used to test this question because astrophysicists think they result from the way dark matter clusters in the universe: the dark matter pulls in ordinary matter, creating the cosmic web and leaving empty spaces behind. But what if general relativity, our best theory of gravity, breaks down somehow over very large distances? Few scientists expect that to be the case, but it has been suggested as a means to explain away the existence of dark matter.

By looking at the thickness of the walls of matter surrounding voids, however, Hamaus and his colleagues determined that Einstein's theory is safe to rely on. To understand why, imagine a void as "a circle whose radius increases with the expansion of the universe," Wandelt says. As the circle grows, it pushes against the boundaries of galaxies and clusters at its perimeter. Over time these structures aggregate, thickening the "wall" that defines the void's edge. Dark energy and neutrinos affect the thickness as well, but because they are smoothly distributed both inside and outside the voids, they have a much smaller effect overall.

Scientists plan to use voids to learn even more about the universe soon because they expect to rapidly multiply the number of known voids in their catalog. “In the next five or 10 years,” Pisani says, “we’re going to have hundreds of thousands. It’s one of those fields where numbers really make a difference.” So, Spergel says, do advances in machine learning, which will make it far easier to analyze void properties.

These exploding numbers won’t be coming from projects explicitly designed to search for voids. They will arrive, as they did with the Sloan Digital Sky Survey, as a by-product of more general surveys. The European Space Agency’s Euclid mission, for example, which launched in July 2023, will create a 3D map of the cosmic web with unprecedented breadth and depth. NASA’s Nancy Grace Roman Space Telescope will begin its own survey by 2028, looking in infrared light. And in 2025 the ground-based Vera C. Rubin Observatory will launch a 10-year study of cosmic structure, among other things. Combined, these projects should increase the inventory of known voids by two orders of magnitude.

“I remember one of the first talks I gave on void cosmology, at a conference in Italy,” Pisani says. “At the end the audience had no questions.” She wasn’t sure at the time whether the reason was skepticism or simply that the topic was so new to her listeners that they couldn’t think of anything to ask. In retrospect, she thinks it was a little of both. “Initially, I think the problem was just convincing people that this was reasonable science to look into,” she says.

That’s much less of an issue now. For example, Pisani points out, the Euclid voids group has about 100 scientists in it. “I have to say that Alice was one of the fearless pioneers of this field,” Wandelt notes about his former Ph.D. student. When they started writing the first papers on void science, he recalls, some of the leading figures in astrophysics “expressed severe doubt that you could do anything cosmologically interesting with voids.” The biggest confirmation that they were wrong, he says, is that some of those same people are now enthusiastic.

Pisani is perhaps the ideal representative for this fast-emerging field. She approaches the topic with absolute scientific rigor but also with infectious enthusiasm. Whenever she talks about voids, she lights up, speaking rapidly, jumping to her feet to draw diagrams on a whiteboard, and fielding questions (of which there are now many) with ease and confidence. She emphasizes that void science won't answer all of astrophysicists' big questions about the universe by itself. But it could do something even more valuable in a way: test ideas about dark matter, dark energy, neutrinos and the growth of cosmic structure independently of the other strategies scientists use. If the results match, great. If not, astrophysicists will have to reconcile their differences to find out what's actually going on in the cosmos.

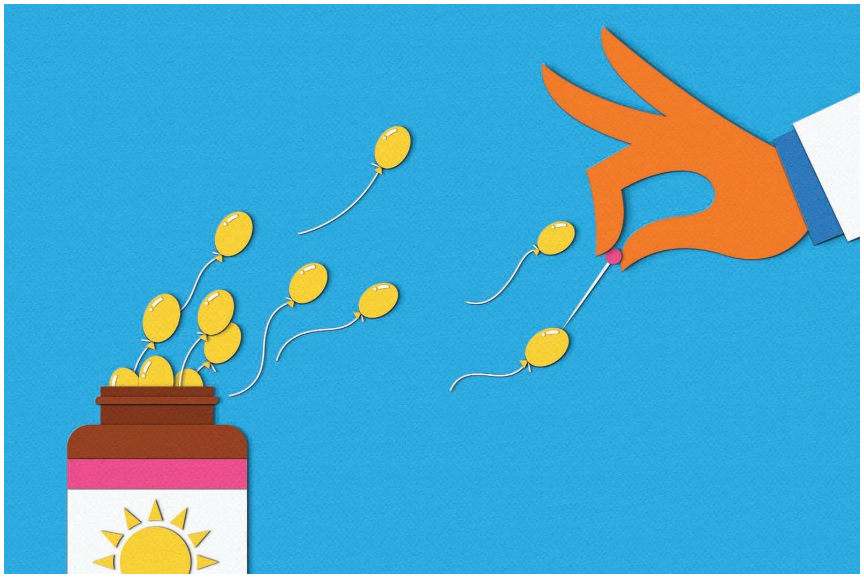
"I find the idea attractive and even somewhat poetic," Wandelt says, "that looking into these areas where there's nothing might yield information about some of the outstanding mysteries of the universe."

Michael D. Lemonick is a freelance writer, as well as former chief opinion editor at *Scientific American* and a former senior science writer at *Time*. His most recent book is *The Perpetual Now: A Story of Amnesia, Memory and Love* (Doubleday, 2017). Lemonick also teaches science journalism at Princeton University.

How Much Vitamin D Do You Need to Stay Healthy?

Most people naturally have good vitamin D levels. Overhyped claims that the compound helps to fight diseases from cancer to depression aren't borne out by recent research

By Christie Aschwanden



Zara Picken

For a while vitamin D was looking like a bona fide health elixir. It was recognized a century ago as the cure for rickets, a childhood disease that causes weak and deformed bones. Then, in the early 2000s, researchers began amassing a pile of studies suggesting that low vitamin D levels could be a factor in cancer, cardiovascular disease, dementia, depression, diabetes, autoimmune diseases, fractures, respiratory illnesses and Parkinson's disease. It seemed reasonable to think that raising our levels of this simple vitamin—one that our bodies make when lit up by sunshine and that we can get more of from supplements—could cure practically whatever ailed us.

At least two books called *The Vitamin D Cure* were published, along with other books and news reports whose titles include words like “revolution” and “miracle.” There was also a growing concern that we weren't getting enough of the vitamin. *Good Morning America* aired a segment that began with reporter Diane Sawyer declaring 100 million Americans were deficient. Her guest was Dr. Oz, who told viewers they could determine their vitamin D level with a simple blood test. Sunshine is the best way to get this vitamin, he said. But if that wasn't enough, he advised cod liver oil or supplements.

Numerous celebrities and vitamin companies raised hopes that vitamin D could be a panacea, says JoAnn Manson, an endocrinologist and epidemiologist at Harvard Medical School and a lead investigator on some of the biggest vitamin D studies to date. Sales of supplements containing the vitamin soared, as did rates of vitamin D testing.

Then the bottom fell out. Although thousands of studies had linked low levels of vitamin D to an assortment of medical conditions, when scientists tried administering it as a means to prevent or treat those problems, the wonder supplement failed miserably. The notion that our lives would be better if we all just raised our vitamin D levels began to look like a fantasy. The idea that vitamin D deficiency was widespread also crumbled. It turned out that notions of what constitutes a deficiency were based on a dubious understanding to begin with. National population sampling showed that most people were already getting enough of the vitamin.

There's no question that vitamin D plays an important role in health. It helps your body absorb and retain calcium and phosphorus; both are critical for building bone. But except for a few subsets of the population (such as breastfed infants and people with particular medical conditions), most people probably don't need supplements.

The story of how vitamin D was discovered, rocketed to miracle status and then returned to Earth illustrates the sometimes jagged path of scientific discovery. It's also a cautionary tale about the need to interpret scientific results with humility. Ultimately it's about the self-correcting nature of science and how knowledge becomes honed over time.

For much of human history, people got their vitamin D mostly from the sun. It turns out humans are a little bit like plants—we can turn ultraviolet light into something our bodies need in a process akin to photosynthesis.

When the high-energy rays of UV light—UVB—hit your skin, they start a chain reaction that converts a compound in your skin called a sterol into a vitamin D precursor. This molecule, after a few more steps, becomes a form of the vitamin that promotes calcium absorption from the gut and increases bone mineralization. Vitamin D also seems to bolster the immune system and tamp down inflammation. It does these things in part by influencing the production of inflammatory compounds and suppressing the buildup of proinflammatory cells. Researchers are studying whether vitamin D can prevent dangerous inflammatory reactions in people with COVID.

Producing vitamin D became increasingly difficult for human bodies during the Industrial Revolution, when smoke and soot darkened the skies and children spent more time in the shade of crowded cities, leading to an increase in rickets. By the late 1800s researchers had documented geographic differences in the prevalence of rickets that pointed to a possible link to sunlight.

In the 1920s Johns Hopkins University biochemist Elmer McCollum identified vitamin D in cod liver oil and gave it its name. German chemist Adolf Otto Reinhold Windaus won a Nobel Prize in 1928 for showing how the body made vitamin D from sunlight. Calling this previously unknown substance a vitamin gave it a sheen of beneficence. The term “vitamin” had been coined by Polish scientist Casimir Funk, who created the word by combining the terms “vita” (Latin for “life”) and “amine” (for amino acids, building blocks of life). The word created “an aura of safety and health,” says Catherine Price, author of *Vitamania: How Vitamins Revolutionized the Way We Think about Food*.

The practice of fortifying food with vitamin D began when McCollum's former student Harry Steenbock, then at the University of Wisconsin–Madison, discovered that he could produce vitamin D in both rats and their feed by irradiating them with UV light. The rays hit sterol compounds, found in the cells of plants, animals and fungi, and start a conversion process. For instance, exposing chickens to UVB light boosts the vitamin D in their meat and egg yolks. Most of the vitamin D in modern supplements comes from irradiated lanolin, a grease derived from sheep's wool. Steenbock also found that feeding dairy cows irradiated feed or mixing irradiated fat extract into milk raised D levels. Today fortified milk and other dairy products—which also use the lanolin-derived form of the vitamin—are some of the most common dietary sources.

In 1936 the Joseph Schlitz Brewing Company introduced “Sunshine Vitamin D” beer. The ads exclaimed that “beer is good for you—but SCHLITZ, with SUNSHINE Vitamin D, is *extra* good for you. Drink it daily—for health with enjoyment.” If it sounds antiquated, consider that in 2022 beer brand Corona launched Corona Sunbrew, a nonalcoholic beer fortified with vitamin D.

Beer is not, however, a health food. The “natural, evolutionarily appropriate way to get vitamin D is through synthesis in your skin,” says Anastassios Pittas, chief of the division of endocrinology, diabetes and metabolism at Tufts Medical Center. But that does not require getting a sunburn. It turns out that you don't need high doses of sun to get sufficient vitamin D. A 2010 study calculated that between April and October, someone in Boston with 25 percent of their skin exposed would need between three and eight minutes of sunlight per day to get enough. Of course, in the winter it might be challenging to find even this amount of sun at some latitudes.

Fortunately, your body is equipped to deal with this kind of variation. Your liver and fat cells store vitamin D for future use, Pittas says. That means you don't necessarily need a big dose every day. Your vitamin D cache generally lasts for about 10 to 12 weeks, so even if you don't have a lot of daily D coming in via sunshine in the winter, Pittas says, you could still have enough circulating from your liver to maintain adequate calcium and phosphorus levels. It's natural to have a winter dip, he says, but that is worrisome only if you're already running low on vitamin D.

Interest in getting extra vitamin D took off when studies suggested it might lower the risk of heart disease, cancer, diabetes, and a range of other conditions.

The problem is that this evidence came mostly from observational studies, a type of analysis that can't show cause and effect and that might produce misleading results, Manson says. These observational studies looked for associations between vitamin D levels and a particular health issue or compared vitamin D status among people with a condition and those without. For instance, an offshoot of the Framingham Heart Study published in 2008 followed more than 1,700 people without prior cardiovascular disease over about five years and found that people with low vitamin D levels had a higher risk of developing heart disease. The results generated a lot of excitement and hype around vitamin D, Manson says.

Diabetes, too, seemed to track with D levels. A study published in 2010 followed close to 6,100 people in Tromsø, Norway, over a period of 11 years. Their incidence of type 2 diabetes showed an inverse relation with blood levels of vitamin D before their body mass was taken into account: higher D levels were correlated with fewer cases of diabetes. Similarly, a 2011 study of more than 6,500 people in Australia found that the risk of developing diabetes over the course of five years was lowest for the participants with the highest D levels.

All these observational studies have a fundamental weakness: they can identify a co-occurrence between vitamin D and a disease, but they can't prove there is a cause-and-effect relation—or, if there is one, they can't identify in which direction it might go. Think of it this way: there's a strong link between someone's wealth and the price of their car, but that doesn't mean buying an expensive vehicle will make you rich.

“Just because you see an association, that doesn't mean that, okay, if we fix the serum vitamin D level, that's going to fix the problem,” says physician Leila Kahwati, associate director of the Research Triangle Institute–University of North Carolina Evidence-based Practice Center. There might be other factors at play. For instance, people who take vitamin D supplements may be more health conscious and do other things that protect them from disease, and people who are already in poor health probably spend less time outdoors getting vitamin D from sunlight.

For these reasons, randomized controlled trials, in which researchers recruit a group of participants and then assign them to receive different treatments (or a placebo), are considered the strongest kind of medical evidence, says physician Jodi Segal, associate director of the Center for Health Services and Outcomes Research at Johns Hopkins University's school of public health. A randomized design makes it much more likely that any differences between the study and placebo groups are caused by the intervention rather than by some other variable.

In 2009 Manson and her team embarked on the world's largest and most far-reaching randomized vitamin D trial, called VITAL. The study followed nearly 26,000 generally healthy adults, randomized to receive either 2,000 international units (IU) of vitamin D or a placebo, for an average of 5.3 years. The volunteers were almost evenly split between men and women, and 20 percent of the participants were Black. The study was designed to look at whether vitamin D supplements could prevent cancer or cardiovascular disease.

The results came as a shock. Not only did vitamin D not make a dent in rates of cancer or heart disease, but the trial also found that vitamin D did not prevent falls, improve cognitive function, reduce atrial fibrillation, change body composition, reduce migraine frequency, improve stroke outcomes, decrease age-related macular degeneration, reduce knee pain or even reduce the risk of bone fractures. The finding about fractures “was a real surprise to many people,” Manson says.

Extra vitamin D also didn't lower diabetes risk. In a trial published in 2019 in the *New England Journal of Medicine*, Pittas and his colleagues randomized more than 2,400 people at risk for diabetes to take either 4,000 IU of vitamin D or a placebo daily. After two and a half years, a similar number of people in each group went on to develop the disease.

The Vitamin D Assessment Study (ViDA) recruited 5,110 volunteers ages 50 to 84 in New Zealand and randomized them to get either a placebo or 200,000 IU of vitamin D per month—a huge dose much higher than the recommended daily allowance. The study found that levels made no difference in cardiovascular disease, acute respiratory infections, nonspinal fractures, falls and all types of cancer. Other trials found that vitamin D supplementation did not reduce mortality rates or the risk of invasive cancer. These results, along with others coming out of VITAL, led to growing skepticism about vitamin D by around 2020, says Clifford Rosen, an endocrinologist at the Maine Medicine Center's Research Institute.

The ViDA trial did find some modest supplement benefits in people who had started the study with a vitamin D deficiency. But what exactly does “deficiency” mean?

It does not mean what many doctors think it does, apparently. The widespread notion that much of America is walking around deficient in vitamin D came from what Manson calls a “misinterpretation and misapplication” of the normal levels for vitamin D set by the Institute of Medicine (IOM, now known as the National Academy of Medicine) more than a decade ago.

Here's what happened. In 2011 the IOM convened an expert committee to conduct a thorough analysis of all existing studies on vitamin D and health. Based on this evidence, the committee concluded that the bone-strengthening benefits of vitamin D plateau when blood levels (as measured by a standard vitamin D blood test) reach 12 to 16 nanograms per milliliter. They also found that there were no benefits to having levels above 20 ng/ml. So they set that as the ceiling for their recommendations while noting that the majority of the population is just fine at 16 ng/ml.

According to measurements of vitamin D levels in the general U.S. population collected through the National Health and Nutrition

Examination Survey, most people had levels of 20 ng/ml or more in 2011. Levels have actually risen since then, meaning that most people are well within the medical recommendations, says Rosen, who served on the IOM committee.

So where did the idea of mass deficiency come from? First off, 20 ng/ml was erroneously interpreted by some health-care workers as the bare minimum, instead of a level marking good amounts for most people. Recall the IOM found that 16 ng/ml was satisfactory. The implication of the misreading was that people needed more than 20 ng/ml for good bone health, Manson says.

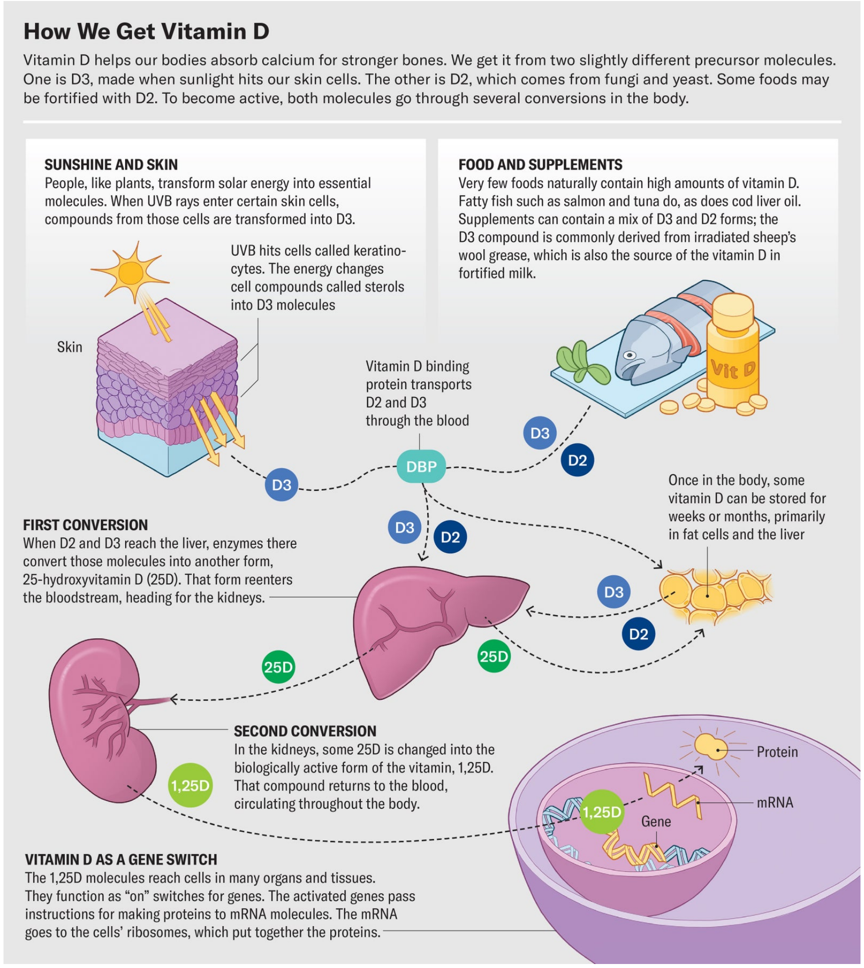
But some of the confusion stems from a second set of guidelines that another medical group, the Endocrine Society, put out around the same time as the IOM standards. Whereas the institute made recommendations for healthy populations, the society's guidelines were aimed at clinicians, particularly those caring for patients at risk for vitamin D deficiency. The makers of these guidelines looked at much of the same evidence that the institute committee reviewed, but they concluded that anything under 20 ng/ml represented “deficiency,” and they labeled vitamin D levels of 21 to 29 ng/ml as something they called “insufficiency.”

The terms “insufficiency” and “deficiency” have created “a tremendous amount of confusion,” says Christopher McCartney, an endocrinologist and clinical research specialist at the University of Virginia School of Medicine. He adds that the Endocrine Society guidelines have been largely taken to mean that everyone needs vitamin D levels of 30 ng/ml or more.

The IOM guidelines don't support that conclusion, and in 2012 the institute committee published a rebuttal paper, “IOM Committee Members Respond to Endocrine Society Vitamin D Guideline.” It contended that aspects of the society's guidelines, including the definition of insufficiency, were not well supported by evidence. For instance, the society's guidelines used a 2003 study of only 34 people to support its contention that vitamin D levels above 30 ng/ml are better for calcium absorption. At the same time the society's committee ignored a study of more than 300 people that found that calcium absorption pretty much maxes out at vitamin D levels of 8 ng/ml.

Michael Holick was the lead author of the Endocrine Society guidelines. An endocrinologist at Boston University's medical school, Holick says that the insufficiency standard is justified by an observational study from 2010. It found that about a quarter of the otherwise healthy adult males had evidence of osteomalacia, a bone-softening condition linked to low vitamin D levels. The study didn't find bone problems in people above 30 ng/ml; hence Holick's contention that 30 was the minimum.

The Endocrine Society is currently in the process of updating its guidelines, with McCartney serving as its methodologist. He says that the new guidelines will focus on randomized trials, not observational ones, and they'll be careful to call out the evidence gaps that remain.



Credit: Now Medical Studios; Graphics consultant: Anastassios Pittas/Tufts Medical Center

The committee is also taking care to avoid outside influence. "Our conflict-of-interest policy is much more transparent and rigorous than I think it has been in the past," McCartney says. Holick, who ran the original guideline-writing group, advocates large doses of vitamin D supplements. Although there is no evidence that his judgments were affected by commercial ties, Holick has received at least $100,000 from various companies involved in making vitamin D supplements and tests, according to a 2018 investigation by Kaiser Health News (now KFF Health News) and the *New York Times*. McCartney says that, in part, concerns raised about Holick prompted the Endocrine Society to pay extra attention to ethics.

Holick made a name for himself espousing the health-promoting powers of vitamin D and wrote a book called *The Vitamin D Solution: A 3-Step Strategy to Cure Our Most Common Health Problems*. He takes 6,000 IU daily and advises his patients to take a minimum of 2,000 to 3,000 IU per day. For comparison, the 2011 IOM report calculated that the average person's daily requirement is 400 IU.

Holick told *Scientific American* that it is “not true” that he has conflicts of interest. He acknowledged receiving industry money but said most of the money had “nothing to do with vitamin D” and was instead “associated with me talking about a new drug coming on the market,” for patients with chronic hypoparathyroidism.

Still, some in the field see Holick's evangelism for vitamin D as conflicting with his role working on the Endocrine Society guidelines. Rosen says that the guidelines “were driven by Mike. He was the chair of the committee.” Rosen trained with Holick and considers him a friend. “He's a good guy,” Rosen says. But “just because you hypothesize something doesn't mean you have to stick with it.... Michael went to extremes to show that vitamin D had something to do with chronic diseases.”

Much of the information put out by companies offering direct-to-consumer testing still claims that anything under 30 ng/ml is low. Athlete Blood Test, for instance, markets blood tests to active people and encourages them to aim for a level of at least 50 ng/ml. While working on this story, I had my vitamin D checked by another testing company, and the laboratory results came back with reference ranges of 30 to 100 ng/ml, implying that anything under 30 was not enough. The lab explanation did note that the IOM's cutoff was 20. (My number was 32.8 ng/ml, which suggests that sunshine really can help—I never take supplements, but I exercise daily outdoors.)

More than 10 million vitamin D tests are done annually in the U.S., despite the fact that these tests are not recommended by major medical organizations such as the Endocrine Society, the National Academy of Medicine and the U.S. Preventive Services Task Force. Three medical societies have endorsed a recommendation to “not order population-based screening for vitamin D” from Choosing Wisely, an initiative to reduce wasteful medical practices.

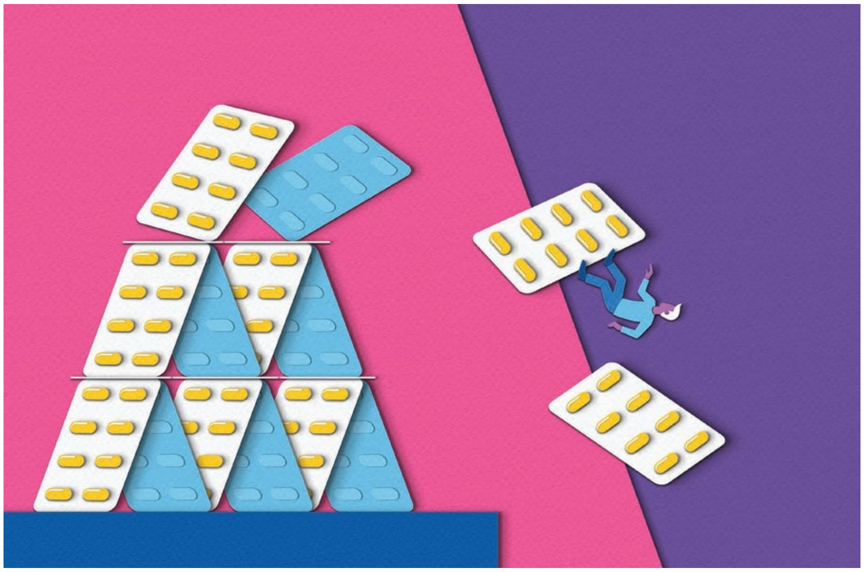
Yet the testing goes on. A study published in 2020 examined medical records from a large regional health system in Virginia and found that about 10 percent of the system's patients were tested for D levels, although many of the tests were not indicated by the patients' health conditions. Supporting the idea of the tests being unneeded, 75 percent of the results came back as normal, says study author Michelle Rockwell, an assistant professor of family and community medicine at the Virginia Polytechnic Institute and State University. Furthermore, some of the test results categorized as abnormal may have been considered just fine by the IOM standards; the study used a higher reference range of 30 to 99.9 ng/ml.

Given the VITAL trial's large size and wide scope, many vitamin D researchers hoped it would put many of the purported benefits of vitamin D supplements to rest. “But there's a religiosity around vitamin D,” Rosen says. Rosen wrote an editorial in the *New England Journal of Medicine* saying most people can stop taking vitamin D supplements and that the large VITAL study was a “decisive verdict.” Even then, he says, he got pushback from colleagues who refused to believe that vitamin D wasn't the panacea they had come to believe. “The evidence is out there,” he says. “People don't want to pay attention to it.”

Although most people don't need supplements, there are exceptions. Breast milk does not contain enough vitamin D for infants, so the American Academy of Pediatrics recommends that babies who are breastfed (partially or exclusively) be supplemented with 400 IU a day of vitamin D beginning in the first few days of life to promote stronger bones. In addition, the academy says all infants and children who consume less than 32 ounces of vitamin D–fortified formula or milk per day should also get supplements of 400 IU. Crohn's disease, cystic fibrosis, celiac disease, and certain liver and kidney conditions can cause vitamin D deficiency, so people with these illnesses might also need supplements. People who are hospitalized or who have had gastric bypass surgery may also become deficient.

Typical tests may, however, overestimate vitamin D problems in some people of African ancestry. The standard test measures circulating blood levels of a vitamin D precursor, 25-hydroxyvitamin D, that is bound to a particular protein. A 2013 *New England Journal of Medicine* study found that some people have gene variants that allow circulation of more of the unbound precursor form and less of the bound one. So by focusing on the bound version, the test underestimates total vitamin D availability. The study, which involved more than 2,000 people, found that those who were Black had lower vitamin D levels than white participants according to the standard blood test. Yet those Black people had strong bones and good calcium levels.

Manson is quick to caution that more isn't necessarily better when it comes to vitamin D. “Vitamin D is essential to good health, but we require only small to moderate amounts,” she says. She doesn't dissuade people from taking supplements of up to 2,000 IU per day, but she doesn't recommend higher levels because some studies have found that excess vitamin D can increase the risk of dangerous falls—researchers speculate that intermittent high doses affect the central nervous system, which could impair balance. And whether you're taking supplements or not, you are probably getting supplemental vitamin D if you consume dairy products, breakfast cereal, plant milks, or other fortified foods, says Price, author of *Vitamania*.


Credit: Zara Picken

Despite the disappointing trials on vitamin D, it's not time to dismiss the vitamin completely, Manson says. There's still plenty more to understand. For instance, the VITAL trial showed that among slender or normal-weight people, defined as having body mass indexes of 25 or less, vitamin D supplements appeared to lower the incidence of cancer, cancer deaths and autoimmune disease. This protective effect did not show up among heavier people with higher body masses. Manson cautions that these numbers need to be verified by further work because they are from a smaller subanalysis of the main study. But it's possible that excess body fat may somehow hamper the effectiveness of vitamin D. Obesity itself is a risk factor for both cancer and autoimmune disease, so it's likely that any connection is complex.

Pittas remains convinced that for people at high risk for diabetes, vitamin D can play a role in prevention. His earlier trial did hint that people who received supplemental vitamin D were less likely to develop diabetes: 24.4 percent of them got the disease, versus 26.9 percent of the placebo group. That difference alone was too small to be statistically significant. But when he pooled the results with those of two other randomized trials, he found a modest but consistent benefit of about a 3 percent reduction in diabetes risk over three years.

There are some positive signs for treating COVID, too. Clinical and lab studies have shown that vitamin D has a positive effect on the immune system and can tamp down inflammation. “We saw this in our VITAL trial,” Manson says. Holick adds that vitamin D can help downregulate so-called cytokine storms, immune system overreactions that have provoked life-threatening respiratory problems in some COVID patients.

Manson's research group has two randomized trials currently underway to test whether vitamin D can help with COVID. One is investigating whether high-dose vitamin D can reduce the chances of getting the extended and debilitating ailment of long COVID. The other trial is looking at whether 1,000 IU of vitamin D per day can reduce the risk of that illness or overall symptom severity. Manson hopes to finish analyzing the data in 2024.

Vitamins hold a certain allure. They're cheap, they're relatively safe, and there's a sense, emphasized by marketers, that they're “natural” and therefore somehow better than drugs, Rosen says. “There's this magical thinking that vitamins improve health, and some people do feel better” when taking them, he says, pointing to the placebo effect as a potential contributor.

The ups and downs of vitamin D offer a lesson in humility. The relation between the vitamin and disease is far more complicated and nuanced than it first seemed and a reminder that scientific understanding is always evolving.

Christie Aschwanden, a journalist and frequent *Scientific American* contributor, is host of Uncertain, a podcast about uncertainty and science. She is author of *Good to Go: What the Athlete in All of Us Can Learn from the Strange Science of Recovery* (W. W. Norton, 2019).

Why Are Alaska’s Rivers Turning Orange?

Streams in Alaska are turning orange with iron and sulfuric acid. Scientists are trying to figure out why

By Alec Luhn

Tukpahlearik Creek in northwestern Alaska's Brooks Range runs bright orange where permafrost is thawing.
Taylor Roades

It was a cloudy July afternoon in Alaska's Kobuk Valley National Park, part of the biggest stretch of protected wilderness in the U.S. We were 95 kilometers (60 miles) from the nearest village and 400 kilometers from the road system. Nature doesn't get any more unspoiled. But the stream flowing past our feet looked polluted. The streambed was orange, as if the rocks had been stained with carrot juice. The surface glistened with a gasolinelike rainbow sheen. “This is bad stuff,” said Patrick Sullivan, an ecologist at the University of Alaska Anchorage.

Sullivan, a short, bearded man with a Glock pistol strapped to his chest for protection against Grizzly Bears, was looking at the screen of a sensor he had dipped into the water. He read measurements from the screen to Roman Dial, a biology and mathematics professor at Alaska Pacific University. Dissolved oxygen was extremely low, and the pH was 6.4, about 100 times more acidic than the somewhat alkaline river into which the stream was flowing. The electrical conductivity, an indicator of dissolved metals or minerals, was closer to that of industrial wastewater than the average mountain stream. “Don't drink this water,” Sullivan said.

Less than a dozen meters away the stream flowed into the Salmon River, a ribbon of swift channels and shimmering rapids that winds south from the snow-dimpled dun peaks of the Brooks Range. This is the last frontier in the state known as “the last frontier,” a 1,000-kilometer line of pyramidlike slopes that wall off the northern portion of Alaska from the gray, wind-raked Arctic Coast.

One of the most remote and undisturbed rivers in America, the Salmon has long been renowned for its unspoiled nature. When author John McPhee paddled the Salmon in 1975, it contained “the clearest, purest water I have ever seen flowing over rocks,” he wrote in *Coming into the Country*, an Alaska classic. A landmark 1980 conservation act designated it a wild and scenic river for what the government called “water of exceptional clarity,” deep, luminescent blue-green pools and “large runs of chum and pink salmon.”

Now, however, the Salmon is quite literally rusting. Tributary streams along one third of the 110-kilometer river are full of oxidized iron minerals and, in many cases, acid. “It was a famous, pristine river ecosystem,” Sullivan said, “and it feels like it's completely collapsing now.” The same thing is happening to rivers and streams throughout the Brooks Range—at least 75 of them in the past five to 10 years—and probably in Russia and Canada as well. This past summer a researcher spotted two orange streams while flying from British Columbia to the Northwest Territories. “Almost certainly it is happening in other parts of the Arctic,” said Timothy Lyons, a geochemist at the University of California, Riverside, who's been working with Dial and Sullivan.

Scientists who have studied these rusting rivers agree that the ultimate cause is climate change. Kobuk Valley National Park has warmed by 2.4 degrees Celsius (4.32 degrees Fahrenheit) since 2006 and could get another 10.2 degrees C hotter by 2100, a greater increase than projected for any other national park. The heat may already have begun to thaw 40 percent of the park's permafrost, the layer of earth just under the topsoil that normally remains frozen year-round. McPhee wanted to protect the Salmon River because humans had “not yet begun to change it.” Now, less than 50 years later, we have done just that. The last great wilderness in America, which by law is supposed to be “untrammeled by man,” is being trammeled from afar by our global emissions.


Scientists compare data at a “burn”—a stretch of thawing ground where seeping water is so acidic it kills vegetation, turning it black. The orange color comes from the presence of iron mobilized by thawing. Credit: Taylor Roades

But how, exactly, permafrost thaw is turning these rivers orange has been a mystery. Solving it is crucial for understanding what the sweeping ecological impact could be and to help communities adapt, such as the eight Alaska Native villages that depend on rivers in the western Brooks Range for fish and drinking water. Some researchers think acid from minerals is leaching iron out of bedrock that has been exposed to water for the first time in millennia. Others think bacteria are mobilizing iron from the soil in thawing wetlands.

I had joined a group of scientists and wilderness buffs for a six-day trip down the Salmon to try to figure out which, if either, of these hypotheses explained the pollution in this once spotless waterway. We'd paddle downriver about 25 kilometers a day, passing from the treeless tundra near its headwaters to the boreal forest at its confluence with the broad, sluggish Kobuk River, then follow the Kobuk to the nearest village. Along the way we'd stop at as many tributaries as possible to take notes, collect vials of water and pick invertebrates off the rocks for the first comprehensive sampling of an entire rusting watershed. If the acid-rock hypothesis proved true, the fish downstream of certain mountains could be in lethal danger. If the bacteria hypothesis was right, the rusting could gradually smother streams almost anywhere there's permafrost—an area that includes about one fourth of the Northern Hemisphere.

To get close to the Salmon, two graduate students and I took a six-seater bush plane inland from the Arctic coast. The ice close to the Salmon had broken up in late spring, so any gravel bars on the river where a fat-tired bush plane might land were still under water. The best the pilot could do was to land on a long, flat gravel ridge in the mist-covered mountains north of the river. The rest of the group, who had been taking data in another watershed, was waiting there for our cargo of inflatable pack rafts, paddles, personal flotation devices, food and 52 water-sampling kits. We strapped the rafts, which folded down to the size of a gallon of milk, to the top of each pack for the hike to the river.

A strip of test paper dipped into a seep at a burn site indicates an acidity around 2.5—like vinegar. Fish and fish eggs in such water would die. Credit: Taylor Roades

“This is the heaviest my backpack has ever been,” graduate student Maddy Zietlow said before we powered through 20 kilometers of windswept ridges, ankle-twisting tussocks and scratchy brush. We finally descended toward the luminescent braids of the Salmon to camp for the night as half a dozen white-coated Dall Sheep bounded away over a ridge.

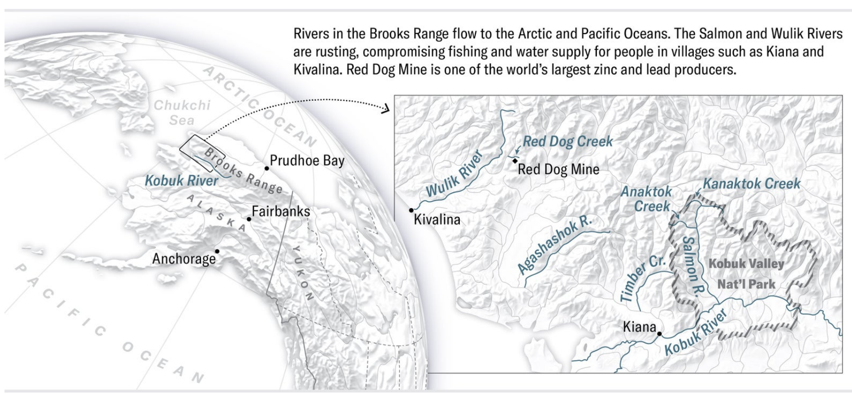
The highest reaches of the Salmon still have clear water, but they're too rocky and shallow to float on, so the next morning we sloshed a few kilometers down the nascent river until we found a spot deep enough to launch our pack rafts. We stuffed the food and gear into oval storage tubes in the rafts and blew them up taut. During the first few kilometers of paddling, we had to lift our butts off the bottom of the rafts to keep from getting stuck every time the current scraped us over a ledge of rapids. We dodged aquamarine marble rocks the size of couch cushions.

When McPhee was here, he wrote that the river was so clear and full of fish that “looking over the side of the canoe is like staring down into a sky full of zeppelins.” These days, however, looking over the side is like staring down into a sky full of thick haze. An hour downstream from where we embarked, a large tributary called Kanaktok Creek was pumping in murky water over orange rocks, turning the Salmon green. The next incoming stream was so full of iron that the main stem ran half orange and half green. For the rest of the trip the river had the color and opacity of pea soup. “Most climate change is subtle,” said Forrest McCarthy, a former U.S. Antarctic Program field-safety coordinator, who was helping with water samples. “This is like, bam!” he continued, snapping his fingers.

The first investigators to document the rusting rivers were U.S. Geological Survey and National Park Service personnel studying how permafrost changes in the Brooks Range are affecting fish such as the Dolly Varden, a big, silvery green char with red spots that local villages prize above all others. In August 2018, when biologist Mike Carey flew by helicopter to retrieve a water sensor he had left in a clean stream east of the Salmon, he saw that the bottom was blanketed in orange slime. He couldn't find any fish or insects. “Biodiversity just crashed,” he recalled.

Carey thought the weird situation was a one-off until the following July, Alaska's hottest month on record. The Agashashok River, 96 kilometers west of the Salmon, turned from turquoise to orange-brown along part of its course. In the winter of 2019 the snowpack was abnormally high; that can insulate the ground, further encouraging permafrost thaw. Then came another hot summer and another snowy winter, and the rusting spread.

Dial and Sullivan, who had been studying the northward march of the tree line in the warming Brooks Range, were shocked by how fast streams there started transforming. On one 2020 expedition the water in a stream called Clear Creek was so acidic it curdled the powdered milk Zietlow used for her nightly tea. A loose network of interested scientists began to coalesce. For Dial, a kind of wilderness beatnik with a face of white stubble and a stream-of-consciousness manner of speaking, the expanding project was personal: he had been climbing mountains and floating rivers in the Brooks Range for more than 40 years. “It's fascinating from a scientific point of view, but from an emotional point of view, it's sad,” he said of the changes he's witnessing. “The alarming thing is how far our human reach is, in a big way.”



Rivers in the Brooks Range flow to the Arctic and Pacific Oceans. The Salmon and Wulik Rivers are rusting, compromising fishing and water supply for people in villages such as Kiana and Kivalina. Red Dog Mine is one of the world’s largest zinc and lead producers. Credit: Daniel P. Huffman

After about four hours on the water, we came to a wide bend where the river looked as if it were disappearing into a tunnel. The current had eaten deep into the softening shore, creating an overhang of earth at least 30 meters long. Muddy roots hung down like strands of a beaded curtain. Globules of watery dirt plopped into the river, and the air smelled like a mix of moldy towels and rotting vegetables—the unmistakable scent of thawing permafrost. “I don't remember that,” Sullivan said, frowning.

Permafrost ranges from isolated patches in Anchorage to a near-continuous sheet in the Brooks Range. If you set a fire and then dug down into the warmed area like gold miners did, under about a meter of seasonally thawed topsoil you'd find ground as hard as concrete and as many as 600 meters deep in places like Prudhoe Bay, much of which has been frozen since the last ice age. Within that layer is animal and plant matter holding twice as much carbon as the atmosphere does. When permafrost thaws, microbes begin to digest this matter and emit carbon dioxide and methane; that rotting-vegetable smell means the planet is cooking.

The ice contains other surprises as well. In Russia in 2016, anthrax reactivated by permafrost thaw led to the death of a 12-year-old boy. The softening earth could also unleash viruses, chemicals or mercury, a recent study warned—a Pandora's icebox of unexpected consequences. Still, the rusting of rivers blindsided the Alaska scientists. They suspected that the thaw was driving it, but they weren't sure how. Then David Cooper, an ecologist at Colorado State University, suggested what they now refer to as the “wetlands hypothesis”—the idea that microbes in the soil are producing not just methane but also soluble iron.

Cooper has known Dial since 1979, when, as a teenage climber, Dial wandered into Cooper's research camp in the Brooks Range soaked, freezing and hungry. He gave the young Dial warm clothes and food, perhaps saving his life. In 2021 Dial invited Cooper on a research trip to Timber Creek, 30 kilometers west of the Salmon. On the first day Cooper tried some fly-fishing and found more iron than fish. “I looked at the creek,” he recalled, “and I said, ‘This creek is dead. It's just blanketed with metals.’”

He wondered whether bacteria might be to blame. The chemical process of breaking down carbon compounds for energy produces hydrogen atoms with an extra electron each. Many bacteria rely on oxygen molecules to accept that extra electron in a process known as reduction. But in waterlogged environments, where there is no free oxygen, bacterial respiration can reduce other elements, such as sulfur, or it can reduce the oxidized iron that, along with organic matter and manganese, gives soil its brown color.

The thaw of permafrost soil under a wetland allows bacteria to start reducing that oxidized iron, Cooper thinks. And reduced iron, unlike oxidized iron, is soluble in water. If it's carried by groundwater out into an oxygenated stream, it can once again be oxidized. When that happens, it will fall out of the water as “rust” and turn the stream orange. While digging trenches on marshy ground near Timber Creek this past August, Cooper and Dial found water as deep as 1.5 meters under the once frozen soil, as well as dirt the gray color of reduced iron. New groundwater flows have developed in the thawing earth, Cooper said, and they have “really awakened a lot of these geochemical processes that have been basically stalled out for 5,000 years because the ground's been frozen.”

The second night, we camped among spindly spruce trees on the gravel shore across from where Anaktok Creek, a toxic orange tributary, runs through a long, winding valley and into the Salmon. Dial and Sullivan, who knew the Anaktok from previous trips, wanted to hike half a dozen kilometers up into the valley and float back down, sampling the creek and the tiny streams that feed it. The next morning we grabbed several water-sampling kits each, paddled across the river, packed up our rafts and started up the northern slope. As we got higher we could see across to the southern side of the valley, and we discovered a startling sight. An expanse of green tundra maybe 100 meters long looked as if it had been burned—only there hadn't been any wildfire.

We scrambled up a hill and began moving along the broad ridgeline, and after more than an hour we came across an ugly black sore on our side of the valley. Twigs of dead lingonberry and dryas shrubs drooped onto dirt the color of fresh asphalt. A channel of water trickled out of the dark ground. It was too shallow to measure with the sampling kit, so McCarthy offered to sacrifice his Nalgene water bottle. He took one last swig and dumped its contents, then slowly refilled it from the seep. When Sullivan dipped a sensor into the bottle, it showed a pH of 2.95, like vinegar.

The burn was from acid. “If it's got that low of a pH ... it's actively burning,” Sullivan said. “There's at least a dozen burns in this valley,” Dial added.

Roman Dial, David Cooper, Dan Gregory and Timothy Lyons (*left to right*) discover water flowing through iron-rich soils in burns as well as wetlands, suggesting different sources of the rusting. A crack indicates the ground is shifting as underlying permafrost thaws. Credit: Taylor Roades

We stumbled on another burn among the raking willow shrubs as we descended toward the creek, and the trickle from the lumpy black crust there was strongly acidic, too. Below the black spots, an orange slime covered the rocks of the Anaktok, rubbing off on the hands of Alexander Lee, an Alaska Pacific University philosophy professor who was helping to sample fish and invertebrates. A small stream coming down from the hills had a highly acidic pH of 3.5. “Wow, this is crazy,” Dial said.

“And not much rust. It's probably still in solution,” Sullivan said. Although the wetlands hypothesis offered a reason for the orange staining, it couldn't explain the acidification. In late 2022 Lyons had contacted Dial with the idea that water was reacting with minerals in the bedrock—the “acid-rock drainage hypothesis.” He had seen a web article with a photograph Dial had taken of the Salmon in autumn, as bright yellow as the Balsam Poplar trees next to it, and he was reminded of research he'd done for NASA on Spain's infamous Rio Tinto, which is so orange and full of acid from upstream mining that it's considered a potential analogue for acidic sites on Mars.

Most ore deposits are rich in sulfide minerals such as pyrite (“fool's gold”), a compound of sulfur and iron. If a sulfide mineral is exposed to water and oxygen, as will happen when miners start breaking up rock, the sulfur splits off the metal and bonds with hydrogen and oxygen molecules, forming sulfuric acid. The resulting contamination by acid and metals, including iron, is a problem in flooded mines and in ponds full of tailings (the waste product from processing mined ore) around the world. Acid-rock drainage can also happen naturally when streams weather sulfide rock in ore deposits. Alaska Natives have spotted occasional orange streams around the Brooks Range for years—though not in the numbers appearing now. Lyons thinks permafrost thaw is lifting the icy lid off the bedrock, allowing oxygenated water to reach pyrite-rich shale for the first time in thousands of years. That's forming sulfuric acid and oxidizing the leftover iron, which would normally precipitate out of the water as rust. The acidity dissolves the oxidized iron, allowing it to flow with the ground seep just as reduced iron does.

But the Brooks Range also happens to have a lot of alkaline limestone, which makes water more basic. If the acidic water from a seep reaches an alkaline river or stream, its pH will rise, and the iron will fall out as what miners would call yellow boy. “It's like a one-two punch,” Lyons said. “You have the shaley rocks with pyrite that source the acid and the iron, and then the limestones neutralize that acid and cause the iron to come out of solution.”

What's really scary is that the acid might also be leaching out other metals, such as copper, zinc, cadmium, lead and even arsenic, that are then carried far downstream. Mining areas often hold enough sulfide minerals to fuel these reactions for millennia. Hillside seeps from permafrost might “turn on” only in years of greater thaw, or they could continue for decades or centuries. “That's why this problem is so challenging from a remediation point of view,” says Brett Poulin, an environmental toxicology expert at the University of California, Davis. “As long as you have water and oxygen and there's still a mineral, it will just keep going.”

For the next two days we kept paddling and sampling tributaries as hills coated only by low groundcover gave way to lowlands of teeming conifers. The Salmon, widening, seemed almost devoid of fish, and the sky was eerily free of birds. After three days of trying, Lee, the philosophy professor, caught only one Dolly Varden, coring a small tissue sample from its polka-dotted side to test it for metals.

The murky water started to clear slightly; clean tributaries were diluting the colored flows. But on our second-to-last day, just before the Salmon joined the Kobuk River, we found the ugliest stream yet, coming out of a marshy woodland. It was more a hideous maroon than orange. Almost like an ooze, it clogged the filter of the water-sampling kit. Saplings along the bank had been chewed by beavers, which have been moving north with the advancing tree line, their ponds further thawing the permafrost. “It's a massive wetland,” Dial said after paddling partway up the stream. “I think what we've got is the wetlands hypothesis.”

This burn may have begun recently because much of the vegetation within it is still green. Credit: Taylor Roades

We pulled into the Alaska Native village of Kiana on the Kobuk at 3:00 A.M. on our final day. By that time we had rafted more than 145 kilometers and sampled more than 20 streams, but we still hadn't solved the mystery. There appeared to be evidence for both hypotheses. In the “valley of the burns,” permafrost thaw seemed to be allowing water to leach iron out of the bedrock, which turned our campfire discussions toward the acid-rock drainage hypothesis. Around the ugly stream, though, it was more likely that permafrost thaw was activating iron-reducing soil bacteria, as the wetlands hypothesis would suggest. In many places, both mechanisms are probably playing a role.

Although the Salmon is a good place to investigate these interactions, it's relatively far from human habitation, and its effluent gets diluted by the massive Kobuk. But as the rusting metastasizes to other rivers in the Brooks Range, it threatens to harm settlements, first and foremost the coastal town of Kivalina.

Like the Salmon, the Wulik River flows down from the Brooks Range, and many of its tributaries have been turning orange. The difference is that at the mouth of the Wulik there is a village, Kivalina, whose 444 residents rely on the river for water and fish. Small changes in water quality could have significant consequences for them.

I flew in a small airplane to the shrinking barrier island north of the Bering Strait where Kivalina is located, about 160 kilometers northwest from where our paddling had ended. The first things I saw on arrival were crosses marking graves on the narrow strip of land along the runway. Behind that was the lagoon where the Wulik empties into the sea.

The next evening Jared Norton, a 25-year-old in a Los Angeles Dodgers cap and white hoodie, pulled up a fishing net across the bow of an aluminum boat, a drizzling rain falling across the lagoon. Like many residents, Norton spends a lot of his time hunting and fishing. The first few fish were silvery Chum Salmon, also known as dog salmon because they're the primary pet food in Alaska Native villages. Then a big fish with a turquoise back and sides came into view. “There's the one I'm looking for!” Norton said. “There is the one I need.” It was a Dolly Varden.

Dolly Varden are a big part of Kivalina's way of life. They're also likely to be the first fish affected by rusting rivers. Chum Salmon leave freshwater for the ocean days or weeks after emerging from the streambed and return only at the end of their life, but Dolly Varden take years to make it to the sea. Once they do, they return to rivers and lakes every year to overwinter. Some “residents” never leave freshwater at all. As a result, they're more exposed to changes in the streams.

A mature Dolly Varden is green with red spots—a beautiful fish, even more striking than its cousin the Brook Trout. The name comes from a Charles Dickens character who beguiles men with her cherry-colored clothes or, more likely, from a red polka-dot fabric inspired by her. Anglers will pay thousands of dollars to fish for one in the Wulik, where a 12-kilogram world-record breaker was caught in 2002. Alaska Natives value the Dolly for its flavorful orange flesh. They say Kivalina's Dolly Varden “taste the sweetest” of all, especially after they've been left to age for two weeks along the shore. Residents trade bags of fish with northern villagers for blubber and with southern villagers for venison.

David Cooper tests for pH levels and for electric conductivity, which can indicate dissolved toxic metals such as copper, cadmium and arsenic. Roman Dial pushes a metal probe a meter down into the ground, where permafrost would have been as hard as concrete if it were still frozen. The gun is for protection against Grizzly Bears. Credit: Taylor Roades

Norton put the Dolly Varden in a metal bucket to take home to his mother. After a few more Chum, a second Dolly came up in the net. This one was smaller, with a reddish mark on its pale belly, like a wound that had healed. Norton hurled it back into the lagoon.

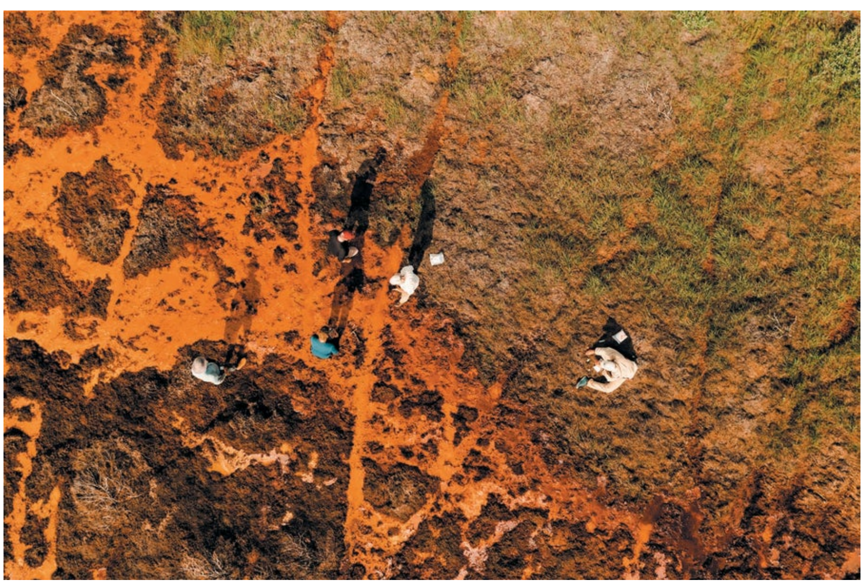
Kivalina is a hard place. With no plumbing, residents have to haul water in barrels. Several houses—prefab wood structures built on short stilts—are cracking as the land sinks and gets eroded, weakened by the melting of sea ice above and permafrost thaw below. Hoping to eventually get enough funding to retreat from the sea, the village has built a school 13 kilometers inland. The “evacuation road” leading to it is already cracking in places from thaw.

Like several other Alaska Native villages, Kivalina depends on rivers flowing out of the Brooks Range for fish and drinking water. For hundreds of years seminomadic Inupiat people came here in the spring to go after northbound whales, then moved inland to hunt Alaska's largest caribou herd as it headed south in the fall. They relied on late-autumn Dolly Varden to get through the nine months of cold.

The people here have managed to keep these hunting and fishing traditions alive despite forced settlement, Christianization, devastation of the whales and a long succession of epidemics. To this day, four fifths of their food come from the land and sea—now via snowmobile and motorboat. But tributaries of the Wulik have begun rusting, possibly jeopardizing the Dolly Varden. “It would be a real big hurt on us,” says Replogle Swan, president of the Kivalina Volunteer Search and Rescue. “That fish is just a part of our lives.”

Iron and other metals can starve fish by smothering invertebrates they eat, such as mayflies, and fish eggs could suffocate if the streambed is covered in iron. Researchers have found that iron and aluminum on fish gills hinder respiration. Cherelle Barr, a mother of two who works for the regional native corporation, fishes rod and reel for Dolly Varden every fall at her family's cabin near the mouth of the Salmon River. Of the 30 Dollies they caught last year, about 10 were deformed, she said. Some had big bumps on their back; others had pus behind their gills. Even bears on a small island in the river were wary. “You could tell they were not eating the [fish] that had that stuff by their gills” or the ones that were deformed, Barr said. The pus could be caused by a parasite or disease, but it is concerning. State scientists who track fish have seen them avoid streams with elevated iron, manganese and acidity.

Since 1989 Red Dog, one of the world's largest zinc mines, has been fundamental to the region's economy. Every year after the ice starts breaking up, the mine, 64 kilometers inland, discharges treated wastewater into Red Dog Creek, which flows into the Wulik and to the sea. Kivalina residents accuse the mine, which in the past has been found guilty of violating the Clean Water Act, of spoiling their water. Some people haul drinking water by boat from another nearby river rather than filling up at the tank supplied from the Wulik.



The researchers collect water samples and data at a rusty seep. They think the straight orange lines may be trails left by caribou, Dall Sheep or wolves. Credit: Taylor Roades

In some ways, however, Red Dog Creek got cleaner after the mine opened because the creek was a natural source of acid-rock drainage before the mine was there. In fact, the creek's orange color was what led a bush pilot to report the likelihood of valuable minerals there in the 1960s. Concentrations of heavy metals downstream declined after the mine installed pipes to divert Red Dog Creek and other streams around the ore deposits, according to annual monitoring by the Alaska Department of Fish and Game. The creek also became less acidic. At the same time, the concentration of “total dissolved solids” increased, mainly because of sulfates and calcium hydroxide the mine was adding to remove metals from the wastewater.

During the hot summer of 2019 the concentration of total dissolved solids downstream rose so much it reached the limit set by Red Dog's permit, forcing the mine to stop discharging its wastewater into the creek for more than a year. The problem was that creeks upstream of the mine were beginning to rust, feeding milky yellow water into the Wulik. Red Dog couldn't start discharging again until it built a $19-million reverse-osmosis treatment system that released cleaner wastewater.

Since then, more streams above the mine have turned orange because of permafrost thaw, Fish and Game says. Total dissolved solids have continued to rise despite the treatment system. “Fish swimming in or through this water would not probably die right away, but it is a chronic stressor,” says Brendan Scanlon, a biologist with Fish and Game in Fairbanks.

Permafrost has become a bigger polluter than the mine, and not much can be done to clean up the problem. Lime is often dumped into tailings ponds at old mines to buffer acid, but you can't “lime” an entire mountain stream, just as you can't refreeze the ground around it. Perhaps the only real hope is that once all the permafrost has thawed and all the iron has rusted, these wild rivers will be able to flush out the contamination and restore themselves, although that would take decades at least.

When we were floating the lower Salmon, in the round-the-clock sunshine of the Arctic summer, I had asked Dial what still fascinated him about the Brooks Range after all these years. He replied that it's how much the vast ecosystem here is changing but also how it has the power to heal. “It's resilient,” he said. Given enough time, he hoped, the wilderness might prove “big enough to clean itself up.”

This story is part of the Pulitzer Center*'s nationwide Connected Coastlines reporting initiative.*

Alec Luhn wrote the feature “Rusting Rivers” in our January 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.

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Intervention at an Early Age May Hold Off the Onset of Depression

Preventing initial episodes might stop depression from becoming a disabling chronic condition

By Elizabeth Svoboda

Andrea Ucini

Esther Oladejo knew she'd crossed an invisible boundary when she started forgetting to eat for entire days at a time. A gifted rugby player, Oladejo had once thrived on her jam-packed school schedule. But after she entered her teenage years, her teachers started piling on assignments and quizzes to prepare students for high-stakes testing that would help them to qualify for university.

As she devoted hours on hours to cram sessions, Oladejo's resolve began to fray. Every time she got a low grade, her mood tanked—and with it, her resolve to study hard for the next test. “Teachers [were] saying, ‘Oh, you can do much better than this,’” says Oladejo, now 18, who lives in Merseyside, England. “But you're thinking, ‘Can I? I tried my best on that. Can I do any more than what I've done before?’”

One morning, as Oladejo steeled herself for another endless day, her homeroom teacher passed out a questionnaire to the students, explaining that it would help assess their moods and well-being. Oladejo filled it out, her mind ticking forward to her upcoming classes.

Soon after that, someone called to tell her she'd been slotted into a new school course called the Blues Program. Developed by Oregon Research Institute psychologist Paul Rohde and his colleagues at Stanford University, the program—a six-week series of hour-long group sessions—teaches students skills for managing their emotions and stress. The goal is to head off depression in vulnerable teens.

Although Oladejo didn't know it at the time, her course was one in an expanding series of depression prevention programs for young people, including Vanderbilt University's Teens Achieving Mastery Over Stress (TEAMS); the University of Pennsylvania's Penn Resiliency Program; Happy Lessons, developed by Dutch social scientists; and Spain's Smile Program. The growing global interest in depression prevention is helping to establish the efficacy of a range of programs in diverse settings.

For researchers heading up depression prevention programs, the stakes of early intervention couldn't be higher. The earlier a first episode of depression begins, and the more episodes a person suffers, the more serious and disabling the condition is likely to be throughout life. People who recover from an initial depression have a 40 to 60 percent chance of a later episode; those with two episodes have a 60 to 70 percent chance of recurrence, and those with three episodes have a 90 percent chance—a vicious cycle that too often ends in chronic illness or disability. And since the COVID pandemic, teens' risk of falling into the cycle has climbed: 42 percent of U.S. high school students report lasting sadness or hopelessness in surveys by the Centers for Disease Control and Prevention, up from 28 percent a decade before.

Prevention courses like the one Oladejo took offer hope to halt this trend. Intervention during the teen years, studies suggest, can potentially stop the kind of depressive cascade that erodes human potential and imposes massive costs on health-care systems. “It's a chronic episodic illness, and relapse is very common,” says Brown University psychologist Tracy Gladstone. “If you can avoid that initial episode, I think you're really setting people on a much better path.”

Courses for at-risk young people have forestalled depression, numerous studies have found, reducing rates of onset by up to half in the months and years following the programs. Yet program developers have struggled to make a convincing case for prevention amid unprecedented levels of need for acute care during an ongoing global mental health crisis.

Feeling like she didn't have much to lose, Oladejo agreed to give the Blues Program a try. The message she was getting from teachers “was like, ‘You've got to get ready, we've got to do this.’ I was 15—I don't really know what I want to do in my life quite yet,” she says. “I was starting to spiral.”

Health experts and political leaders have been brainstorming ways to ward off mental illnesses such as depression, bipolar disorder and schizophrenia for decades. In a 1963 speech to Congress, President John F. Kennedy described plans for a comprehensive preventive approach at the federal level. The initiative would include “selected specific programs directed especially at known causes” of mental illnesses, Kennedy proposed, but would also involve “the general strengthening of our fundamental community, social welfare, and educational programs.”

Such plans stalled during economic crises in the 1970s. Under President Ronald Reagan, federal spending on social programs decreased, and national mental illness prevention mostly receded into the background.

But rising rates of mental illness through the 1990s, especially in young people, helped to rekindle broader interest in prevention. In a 1994 report called “Reducing Risks for Mental Disorders,” the Institute of Medicine (now the National Academy of Medicine) argued for assessing people's mental health vulnerabilities early in life to stave off the worst outcomes.

By the late 1990s and early 2000s researchers were testing several prevention programs for depression, one of the most common mental disorders. Many of these programs were rooted in the cognitive-behavioral practice of correcting harmful thinking patterns—an approach that has consistently reduced depressive symptoms in studies. Among the first prevention offerings were the Penn Resiliency Program, a series of 12 group classes lasting 90 minutes each, and the Australia-based Resourceful Adolescent Program, consisting of 11 group sessions of 50 minutes.

Around this time Rohde was a young psychologist at the Oregon Research Institute (ORI), a small company with National Institutes of Health funding. Early in his career, Rohde had helped develop Adolescent Coping with Depression, one of the first standardized group treatments for depressed teens.

When psychologist Eric Stice joined Rohde's research group in the mid-2000s, Rohde and his colleagues started focusing on depression prevention. Stice specialized in preventing eating disorders, and his graduate student Sarah Kate Bearman wanted to see how much a similar approach could help teens on the cusp of depression. Bearman's graduate thesis described an early iteration of the Blues Program, teaching teens cognitive-behavioral skills in four one-hour sessions. Rohde liked the way this program component condensed cognitive principles into digestible lessons—and he liked that it took less time than competitors such as the Penn Resiliency Program, which could make it easier for schools and agencies to implement.

After Bearman graduated, Rohde, Stice and Stanford researcher Heather Shaw continued to develop the Blues Program and test it at a number of pilot sites. Having watched depression disrupt his clients' lives year after year, Rohde was fired up about the idea of bending teens' mental health curve for a lifetime. “We know that if we can prevent depression in young adulthood, we're going to prevent recurrent episodes of depression,” he says. “We're going to reduce future suffering.”

It makes intuitive sense that preventing a first depressive episode could reshape someone's mental health trajectory. Less intuitive, and less well known, are the biological stakes involved in keeping depression at bay. During each bout of depression, brain tissue can shrink—especially in the hippocampus and prefrontal cortex, which govern memory, emotion and higher-order thinking. It's unclear whether this brain atrophy can be fully reversed. The decrease in tissue is also linked to future bouts of depression. In recovered people who relapsed, the brain's cortical volume shrank over a two-year period, whereas recovered people who did not relapse showed no such change.

Brain changes during adolescence may make teens especially vulnerable to depression and the cellular havoc it wreaks. In a study from McLean Hospital in Belmont, Mass., young people who experienced hardship such as emotional abuse at age 14 or 15 were more likely to become depressed compared with those who faced such adversity earlier or later in life. Prolonged stress, research shows, may be more damaging to the brain during this time—and another study suggests that early stress-linked brain changes may make people more vulnerable to depression.

Rates of depression steadily climb during the teen years, so some specialists contend that the earlier teens enroll in prevention programs, the better. “The adage that an ounce of prevention is worth a pound of cure is really true in this setting,” says adolescent psychiatrist Elizabeth Ortiz-Schwartz of Silver Hill Hospital in Connecticut. “We need to start looking at early adolescence.” Rohde concurs, which is why he, Stice and Shaw designed the Blues Program to serve students as young as 12. The first step in Blues—now offered at sites in Pennsylvania, Texas and Utah, as well as in the U.K.—is screening school populations for high-risk students like Oladejo. These students report sleep problems, low self-esteem or low interest in daily activities, but their symptoms aren't severe enough for a depression diagnosis. (Some symptoms rule teens out of the program; if they report feeling suicidal, they're referred to acute treatment.) Gauging students' distress from the questionnaire works better than probing into their family histories. “For us, it's easiest just to ask the student if they have some symptoms,” Rohde says, adding that when teens are struggling, “that provides motivation for working on skills.”

From there, facilitators organize qualifying students into small groups and teach them cognitive tactics they can use to process difficult events. Many of these measures resemble those therapists teach depressed clients, but the Blues Program introduces them as a kind of vaccination strategy. When teens learn how to keep stress in check, the theory goes, they'll be able to defuse new stressors before their emotional impact explodes.

One teaching tool in the program is the “triangle of feelings, thoughts and actions,” which illustrates that the way people think about what happens influences how they feel overall—and, by extension, how motivated they are to take helpful action. A negative thought—such as “No one loves me” after a romantic rejection—can make you feel miserable, and when you feel miserable, you'll be less likely to risk asking someone else out. Thinking of the rejection as a painful episode that you can get through, in contrast, can stop the cycle of misery.

The triangle concept clicked for Esther Oladejo. “It basically made you think, Do I want this small situation to dictate how the rest of my life's going to go?” Oladejo says. She could see how her own reactions followed the pattern: after she flubbed an assignment, she'd beat herself up and feel worthless, and that sense of worthlessness made it hard to tackle the next round of papers and tests.

In later sessions of Blues, facilitators explain how to challenge negative thoughts—for example, by brainstorming a new thought that's less exaggerated and more optimistic than the original. “Is there another way to think about this situation?” session leaders ask. “What advice would you give a friend who was feeling the way you do?”

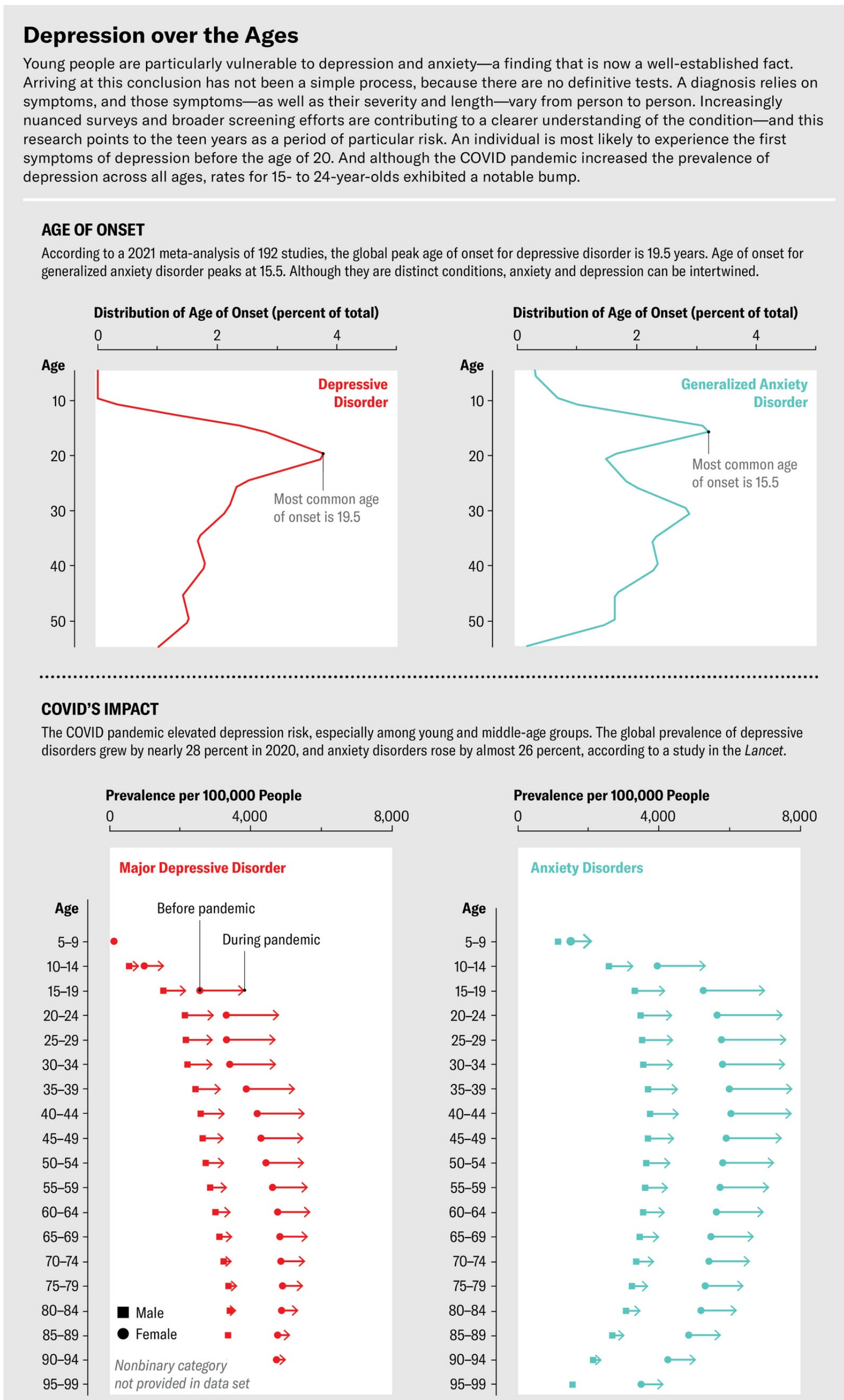
After that, students share their new thoughts with the rest of the group. For Oladejo, an initial gut reaction—“I tanked that test. I suck at school”—might morph into “This isn't my final exam. I can learn from this and do better on the end-of-year test." It isn't the precise content of the revamped thought that matters. "There is not a single right counterthought to a given negative thought," group leaders tell students. "Figure out whether a particular new thought makes sense to you."

The Salt Lake County Department of Youth Services (DYS) occupies a cluster of squat tan buildings ringed by distant snow-topped mountains. Dozens of students congregate there every semester, virtually and in person, developing new cognitive skills designed to help them evade depression. A blue "Heroes Work Here!" banner hangs in the front lobby, where I meet Jodi Rushton, the effervescent social worker who heads up Salt Lake's version of the Blues Program. She leads me into a bright classroom, the table stacked with sandwiches and chip bags for the teens who'll drop in this afternoon.

Rushton tells me that the DYS serves a population at risk for mood disorders—about one in three Utah teens report depressive symptoms—and the Blues Program seemed like a natural fit when she saw it on a list of evidence-based options several years ago. "We were teaching pretty outdated programs," Rushton says. "We needed a revamping."

Enrollment in the program, which DYS staff have renamed "Me Time," has climbed since its inception, and hundreds of local teens have so far completed the course. After COVID hit in 2020, Rushton and her colleagues scrambled to transfer the program online. They worried Me Time wouldn't translate well into virtual space, but their worries were unfounded. In fact, the opposite was true: As soon as DYS started offering online sessions, enrollment exploded. "It just took off. Transportation, space, time—all these obstacles were eliminated," Rushton says. "Even after I close registration, I still just get referrals continuously." She has let teens from other states sign up for Me Time because most have no similar option available locally.

Rushton has a cardinal rule when she leads a session, whether online or in person: Make sure each student gets at least one chance to hold the floor. “It's really interactive,” she says. “A lot of the effectiveness falls on how much attention you can give to everybody—drawing out the teens who maybe are more shy, handling the ones who want to talk all the time.”



Credit: Jen Christiansen; Sources: “Age at Onset of Mental Disorders Worldwide: Large-Scale Meta-analysis of 192 Epidemiological Studies,” by Marco Solmi et al., in *Molecular Psychiatry*, Vol. 27; June 2, 2021; “Global Prevalence and Burden of Depressive and Anxiety Disorders in 204 Countries and Territories in 2020 Due to the COVID-19 Pandemic," by Damian Santomauro et al., in *Lancet*, Vol. 398; October 8, 2021 (*data*)

After chatting with Rushton, I meet a few local Me Time participants ranging in age from 12 to 17. To protect student privacy, the program is closed to outside observers, but the students told me about the dynamic it fosters. "Everyone knows, like, 'Think really deeply about if a problem's as big as you think it is,'" says Monica, the oldest of the group. But the program sessions, she continues, helped her transition from knowing what she *should* do to actually doing it. "It was really helpful to be able to discuss personal experiences and how we could have changed the way we were thinking," she says. "Being able to have a group discussion allowed it to stick more. I've kind of taken it to self-reflect every day: 'Is my reaction fitting the size of this issue?'"

Teens could also learn cognitive-behavioral skills one-on-one with a therapist. But in general, individual therapy can impose a high cost burden on families—and some Salt Lake teens say they like Me Time better than traditional therapy, which tends to have an uneven power dynamic between therapist and client. Me Time "just helps more," one participant tells me. "You're not put on the spot, and you're able to form a connection with other people." The give-and-take spirit of Me Time chats helped another student feel less isolated in their mental health struggles. "You could hear other people's situations—how they coped with it or what they did to solve the problem. If it was just one-on-one, I don't think I would have been helped as much."

Having watched countless Blues Program sessions in action, Rohde agrees. There's something alchemical, he thinks, about teaching cognitive skills in a small-group context. "Part of the value is getting kids together," he says. "As they feel comfortable, they can share the thoughts and feelings and actions that they're struggling with. That can be helpful for the other students because it normalizes that these kinds of problems are really, really common."

Like her counterparts in Salt Lake City, Esther Oladejo drew more than she'd expected on the well of support from her small group. She didn't know most of the other students in her Blues class well at first, but their shared trust grew. When other group members shared school or family problems, she advised them as best she could—and felt gratified when they came back to report that her suggestions had helped. In return, they buoyed her in the same way. “I feel like that's really important—someone who's looking at you as if they actually see you,” she says.

School systems in Utah, the U.K., and elsewhere have adopted the Blues Program in part because of the evidence for its effectiveness, Rohde says. After the ORI team secured funding from the National Institutes of Mental Health, they launched a large-scale 2015 Blues Program trial that enrolled 378 Oregon students at risk of depression. Just 10 percent of students who finished the Blues Program had developed depression by the two-year follow-up mark, compared with 25 percent of control group members who read a cognitive-behavioral self-help book called *Feeling Good*.

A 2018 meta-analysis of four separate Blues Program trials showed that enrolled students were substantially less likely than control subjects to develop depression within two years. Other prevention programs for students at risk, including the Penn Resiliency Program, have also significantly reduced students' depressive symptoms, as have offerings such as Op Volle Kracht (At Full Force) in the Netherlands and Spain's Smile Program.

Salt Lake City's Blues Program site results have largely mirrored these broader ones. During the 2021–2022 school year, students scored notably lower on a standard depression symptom scale after finishing the program, and their scores remained almost as low three months later. And Me Time's new online format seems to work as well as the traditional one: after the program, online participants' depressive symptom scores actually dropped more than those of in-person students. Still, how long these benefits will last remains unknown because studies have not yet been done to assess how many depressive episodes any of these programs might prevent over a lifetime.

The programs that don't hold up as well in trials, at least so far, are those designed to prevent depression in entire school populations. A meta-analysis of more than 40 studies found that schoolwide prevention programs were significantly less effective at staving off depressive symptoms than targeted programs for at-risk young people. Schoolwide programs, Brown University's Gladstone notes, enroll more students who don't have symptoms—and who may therefore be less motivated to master the skills taught in depression prevention programs. “One of the things about these interventions is that they take work,” she says. “It's hard to engage in something when it doesn't have any resonance for you.”

Further trials are underway to determine which program components are most crucial for effective prevention. Along with her colleague Benjamin Van Voorhees, Gladstone has launched a controlled trial comparing two different online depression prevention programs for at-risk students: Teens Achieving Mastery Over Stress (TEAMS) and a self-guided course called CATCH-IT. The study—which has enrolled more than 500 teens from western Illinois, Chicago and Louisville, Ky.—will track not just their depressive symptoms after the programs but how they deal with stress and low moods. So far Gladstone hasn't had any trouble recruiting trial subjects. “It's really difficult to find mental health support,” she says. “Families are just excited about the trial. They want their kids in.”

Despite bursts of local enthusiasm for prevention programs, few school districts or agencies, whether in the U.S. or abroad, have programs like TEAMS or Blues available for struggling teens, and most people are not even aware that such programs exist.

The hard part of broadening the programs' reach, as Gladstone and Rohde have found, isn't convincing teens or families to give them a try. It's convincing those in power that the programs are practical and affordable for resource-strapped communities—and that prevention is worth investing in. Aside from a small one-time fee, schools and nonprofits don't need to pay licensing fees for Blues Program material. But ORI charges organizations $2,800 to train their staff on how to deliver the Blues content to teens, and each local facilitator who wants to instruct other staff must pay thousands more to get certified as a “trainer of trainers.” Administering the program adds to the workloads of counselors, social workers, and other staff, which can oblige managers to pay for more staffing hours or hire more employees.

In general, Gladstone says, depression prevention programs are easiest to implement in countries with national health insurance systems, such as the U.K. These systems, figuring the programs will eventually lead to lower costs for mental health care, are more apt to fund local agencies or nonprofits that offer the programs.

In the U.S., however, “insurance is generally attached to people's jobs, and people switch their jobs,” Gladstone says. “Often there's not really an incentive for insurance companies to fund prevention programs, because by the time somebody would develop the [condition] you're trying to prevent, somebody else will be paying for the treatment.” Although some U.S. insurance companies have started funding exercise programs that prevent physical illness, they don't reliably reimburse providers or agencies for depression prevention programs.

That typically leaves local governments, school districts and nonprofits on the hook to fund prevention efforts. Me Time is in a fortunate position, drawing from the DYS's annual mental health prevention budget of more than $570,000. Across the region, Rushton is trying to increase access to program resources by devoting more time to “training trainers”—briefing school staff members across the Salt Lake region so they can deliver the course to their own students. But this can be a challenging process, she says. “Social workers and counselors, people in schools, are really weighed down. And so even asking them, ‘Hey, we want you to teach this six-week class’—it's kind of a big ask.”

To help make the Blues Program more feasible on a local level, Rohde wants to do more real-world data collection on the practical side of depression prevention programs—how much they'll cost per student, for instance, and how that compares with the cost of treating an already depressed teen. Those kinds of concrete numbers could help convince local decision makers to support the program and health insurance companies to reimburse for it, he says. “It gives them the kind of data they need to say, ‘We're going to prevent this much future treatment cost down the road.’”

But Janet Welsh, principal investigator for Penn State University's Evidence-Based Prevention and Intervention Support program, points out that cost-savings numbers wouldn't necessarily drive wider adoption for depression prevention programs. “To be perfectly honest, I have those data for substance abuse,” says Welsh, who regularly evaluates research-based mental health programs. “I can show you how much it saves to do universal prevention. Yet people still won't do it.”

That reluctance, Welsh says, stems from a basic feature of human psychology: the tendency to value in-the-moment problem solving over avoiding future crises. “Prevention of anything—violence, drug abuse, mental health problems—is always going to be [the less favored option],” she says. If a depressed teen goes to therapy and gets well, her providers can document a clear trend of recovery. But if a student takes a depression prevention course and remains well, it's a different, lowercase kind of triumph, one that can be hard for funders to appreciate when their communities are in mental health crisis. “I can point to some really well-adjusted kids and say, ‘Look, they don't have substance abuse or mental health problems,’” Welsh says. “And you're like, ‘Yeah? So?’”

Despite the challenges of making the case for prevention, Rohde, Gladstone, and others hope that more communities will buy into it—especially given the strong enrollment Blues Program sites have seen since the COVID pandemic began. Clinicians also see opportunities for further honing the programs to attract newcomers, taking steps such as tailoring curricula for students from different backgrounds. A program that works well in California's Bay Area won't necessarily land in urban Detroit, rural England or Alaska Native communities. “Investing in the research and application of those programs is going to be essential,” Ortiz-Schwartz says, “so that districts can find solutions that are more on target with their population.”

Although more data and customized lesson plans may help make the case, those in charge of funding may ultimately look to the human element: how students like Esther Oladejo fare as they approach adulthood. Although Oladejo's mood still drifts up and down at times, she says disputing negative thoughts about her own abilities has given her courage to speak up more and take chances. “Before I probably would have hid away,” she says. “But the structure of being able to think, ‘Okay, what are the benefits? Am I going to be okay doing it?’ Yeah. Let's go.”

That willingness to advocate for herself led Oladejo to an unexpected breakthrough. After finishing the Blues Program and enrolling in college, she continued to flounder academically, and she grew more aware of the mismatch between the hours she put in and the results she was getting. *If what you're doing isn't working*, Blues lessons had prompted, *what are some other ways of solving the problem?* She decided to approach a tutor on her college campus to explain her dilemma, and the tutor referred her to the campus support team. After some tests, they told her she had dyslexia, which helped her get proper assistance—and finally make sense of why school had been such a struggle. (It's common for those at risk of depression, like Oladejo, to have other conditions like dyslexia, ADHD or anxiety; the U.S. Preventive Services Task Force has called for kids and teens to be screened for both depression and anxiety so they can get fast, effective treatment.) “I'd put myself down, thinking, ‘Why can't I just get it the first time around?’” Oladejo says of her academic troubles. “But because I was able to use the skills, not be so anxious to ask for help, I was able to get a diagnosis.”

This progression reveals how the decisions people make in one moment, like Oladejo's choice to speak up and get evaluated for learning challenges, lead to a different array of options than those they'd have if they hadn't made that fateful decision. In that sense, it isn't just cognitive skills or stress regulation or a support group atmosphere that counts for teens at risk of depression. It's the way those things equip them to make choices that alter the decision tree itself. For adults who first slid into depression in middle or high school, it's an absorbing thought experiment: If I'd known how to approach that setback differently, how would my choices have been different? And what other choices would have opened up? And *then*, and *then?*

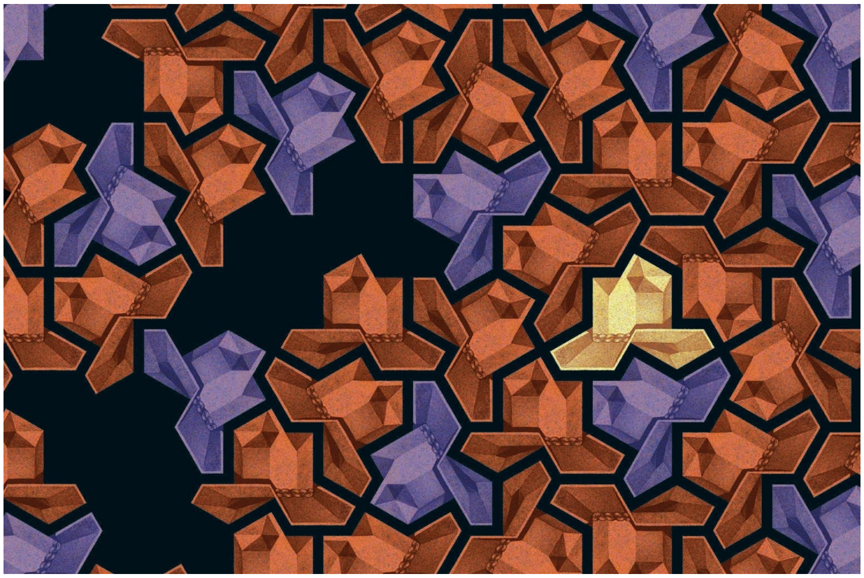
It's in the unfolding of these sequences that the promise of prevention is clearest. To help initiate such sequences for others, Oladejo has volunteered with the U.K.-based nonprofit Action for Children, speaking with local officials and lawmakers about her Blues Program experience. She might pursue a psychology doctorate so she can become a therapist—and she has a clear vision of the work she wants to do, helping clients build the kind of group support structure that got her through her own worst days. “I don't want to be like the usual therapist. If I do face-to-face, I want it to be an inclusive session,” she says. “I want to be able to give people that sense they're not alone.”

Elizabeth Svoboda is a science writer in San Jose, Calif., and author of *What Makes a Hero?: The Surprising Science of Selflessness* (Penguin Group, 2013).

Inside Mathematicians’ Search for the Mysterious ‘Einstein Tile’

The quest for the einstein tile—a shape never seen before in mathematics—turned up even more discoveries than mathematicians counted on

By Craig S. Kaplan



Miriam Martincic

In November 2022 a colleague of mine casually asked what I was working on. My dazed answer reflected the swirl of ideas that was consuming all my mental energy at the time: “Actually, I think the solution to a major open problem just fell into my lap.” A week before, I had received an e-mail asking me to look at a shape. That was the first time I saw “the hat,” an unassuming polygon that turned out to be the culmination of a decades-long mathematical quest.

The e-mail came from David Smith, someone I knew from a small mailing list of people interested in tilings—different ways to arrange shapes to cover a flat surface. Smith isn't a mathematician;

he is a self-professed “shape hobbyist” who experiments with geometry in his spare time from his home in Yorkshire, England. After Smith sent me the hat shape he'd been playing with, we began corresponding regularly, spending the rest of 2022 studying the hat and its properties. In 2023 we reached out to two additional researchers, mathematician Chaim Goodman-Strauss and software developer Joseph Samuel Myers, both also members of the mailing list and well known in the larger world of tiling theory. The four of us continued to study the hat and, in what felt like record time, succeeded in proving that the shape was a long-sought object that many assumed couldn't exist: an aperiodic monotile, also known as an einstein tile.

Credit: Jen Christiansen

On supporting science journalism

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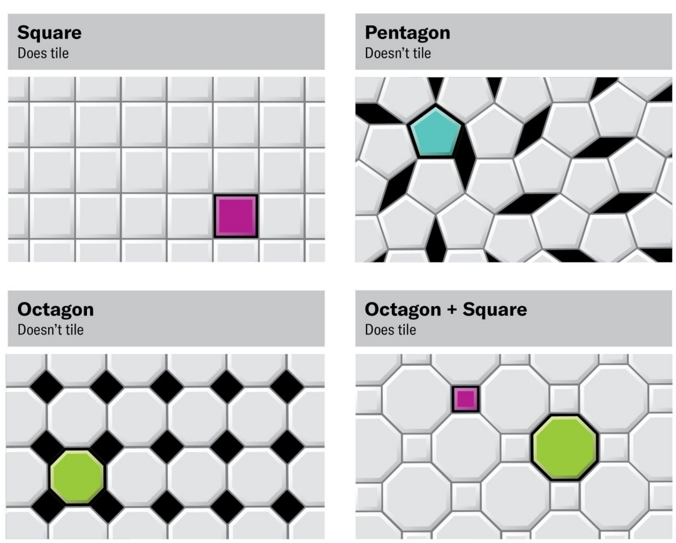
As it turns out, Smith's hat was just the beginning of a sequence of revelations. As we explored the new landscape of ideas revealed by this shape, we were surprised multiple times by additional discoveries that further deepened our understanding of tiling theory. Soon the hat led to “turtles,” “spectres,” and other wonders that yielded more insights than we could have expected at the outset.

Tiles have fascinated humans since ancient times, but mathematicians began studying them in earnest in the 20th century. A so-called tiling of the plane is an infinite collection of shapes that cover a flat surface with no gaps and no overlaps. I will focus on cases where the infinitely many tiles in a tiling come in a finite number of distinct shapes. Imagine a handful of templates that can be used to cut copies of the shapes out of an unlimited supply of paper. Our goal is to arrange cutouts on an infinite tabletop so that every bit of table is covered by exactly one layer of paper. We can move each cutout into position through some combination of reflection (flipping the paper over), rotation (turning it in place) and translation (sliding the shape around without turning it). If we achieve our goal of constructing a tiling, we say that the set of shapes “admits” the tiling and, more generally, that the shapes tile the plane.

Not all sets of shapes admit tilings. A square yields a tiling resembling graph paper, among other patterns, and is therefore a monotile: it tiles the plane on its own (as a set of one). A regular pentagon, in contrast, cannot tile the plane by itself. Neither can a regular octagon, although a two-element set consisting of an octagon and a square does tile.

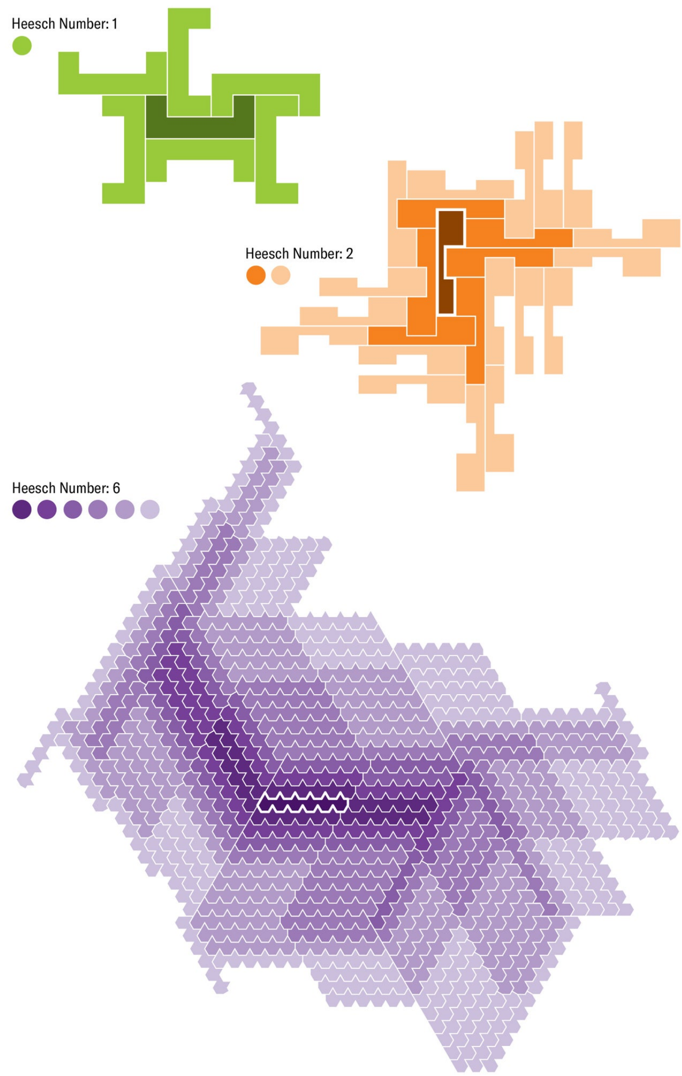


Credit: Jen Christiansen

How can we determine whether a given set of shapes tiles the plane? There's no algorithm we can use to answer this question, and in fact none could exist—the problem is what's known in theoretical computer science as “undecidable.” Nevertheless, we can study individual sets and attempt to build tilings through trial and error or other methods. Along the way we often encounter fascinating examples of how local interactions (the different ways two tiles can sit side-by-side) influence global behavior (the large-scale structure of the tiling out to infinity in every direction).

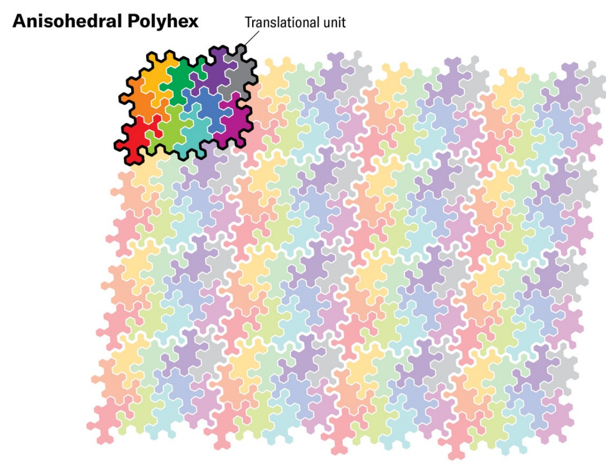
There are multiple ways to figure out whether a single shape can tile the plane. Some people, such as Smith, will even cut out physical paper copies of a shape using a computer-controlled cutting tool and play with them on actual (regrettably finite) tabletops, recruiting the immediacy of touch to augment visual intuition. In the hands of a skilled explorer like Smith, a shape will disclose its tiling secrets in short order. And in the pre-hat era, a shape would invariably behave in one of two ways.

The first possibility is that the shape will not tile the plane. As a quick test, we might try to surround it completely by copies of itself; if we can't, then the shape certainly does not admit any tilings. For instance, the regular pentagon is unsurroundable, which immediately outs it as a nontiler. But although surroundability provides evidence of tilability, it is not firm proof: there are deceptive nontilers that can be completely surrounded by one or more concentric layers of copies before getting irretrievably stuck. In 1968 mathematician Heinrich Heesch exhibited a shape that could be surrounded once but not twice and asked whether there was an upper limit to the number of concentric rings one might build around a nontiler, a quantity now known as a shape's “Heesch number.” The current record holder is a particularly ornery polygon with a Heesch number of six, discovered in 2020 by Bojan Bašić of the University of Novi Sad in Serbia.



Credit: Jen Christiansen

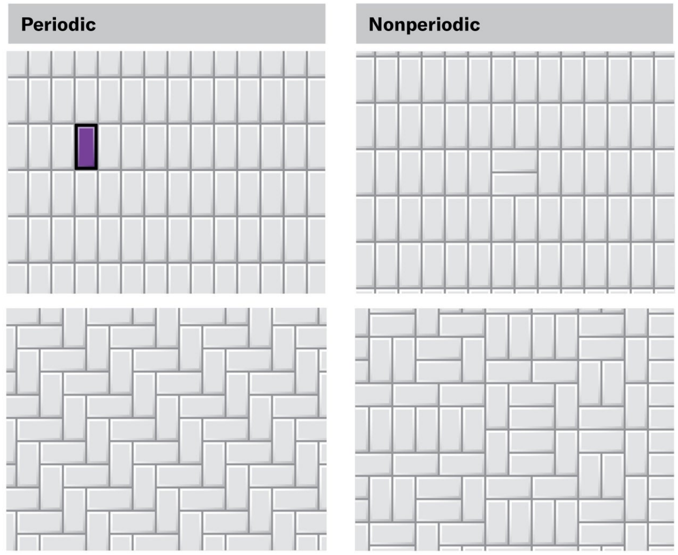
The second possibility is that the shape tiles the plane periodically. In a periodic tiling, the arrangement of tiles repeats in a regular pattern determined by an infinite grid of parallelograms. We can describe a periodic tiling using three pieces of information: a finite cluster of tiles called a translational unit and two line segments that define the sides of a parallelogram in the grid. We can slide a copy of the translational unit out to every vertex in the grid, without rotating or reflecting it, and these copies will interlock to complete a tiling. This method offers a quick test of a shape's ability to tile: we assemble candidate translational units and then see whether any of them covers the plane by repeating in a regular grid. As with Heesch numbers, no one knows whether there is any bound on the smallest translational unit a shape might require before it can be repeated to tile the plane. Myers discovered the current record holder, a shape whose simplest translational unit contains 10 tiles.



Credit: Jen Christiansen

When Smith began experimenting with the hat, what caught his eye was that it refused to conform to either of these options. The hat did not obviously tile the plane: he couldn't find a way to build a translational unit of any size. But it did not obviously *fail* to tile the plane, either: with effort, he could surround a hat with multiple layers of copies without getting stuck. It was conceivable that the hat might be a nontiler with a high Heesch number or a periodic monotile with a large translational unit, but Smith knew that such cases were rare. He reached out to me because he also knew that there was one other possibility, one so extraordinary that it demanded to be considered in full.

About 60 years ago mathematicians started wondering whether there were sets of shapes that could only tile the plane without ever repeating periodically—that is, that someone could assemble copies into arbitrarily large patches without ever encountering a translational unit. Such a set is called aperiodic. Crucially, aperiodicity is a much stronger property than nonperiodicity. Lots of shapes, including a humble 2 × 1 rectangle, can admit tilings that are periodic as well as tilings that aren't periodic. Aperiodic sets have no possible periodic tilings.

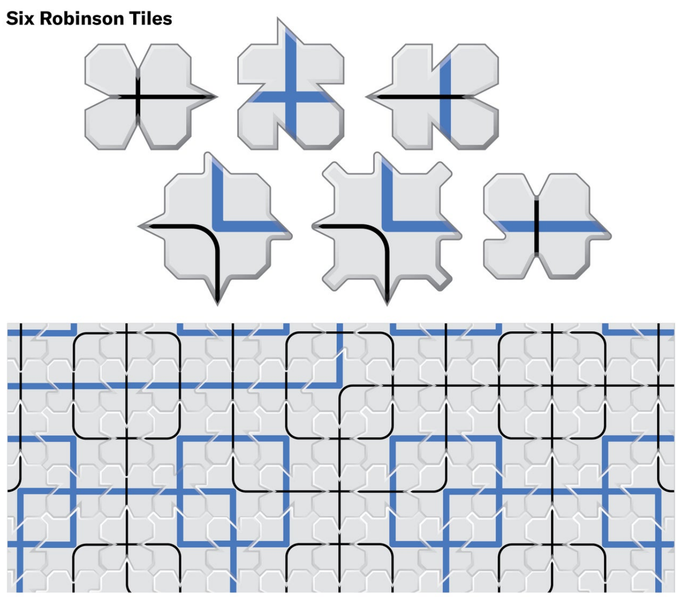


Credit: Jen Christiansen

The notion of aperiodicity was first articulated by Hao Wang in the early 1960s, while he was a math professor at Harvard University. He was studying what we now call Wang tiles: square tiles with symbolic labels or colors on their edges that must be positioned so that neighboring squares have the same markings on their adjoining edges. (These labels are a convenient shorthand for equivalent rules that can be expressed geometrically.) Wang observed that if, given a set of tiles, one can find a rectangle whose top and bottom edges have the same sequence of labels and whose left and right edges also match, then that rectangle is a translational unit, and hence the set tiles the plane. He then conjectured the converse: that if a set of Wang tiles admits a tiling of the plane, then it must be possible to build such a rectangle. In other words, he claimed that Wang tiles can never be aperiodic.

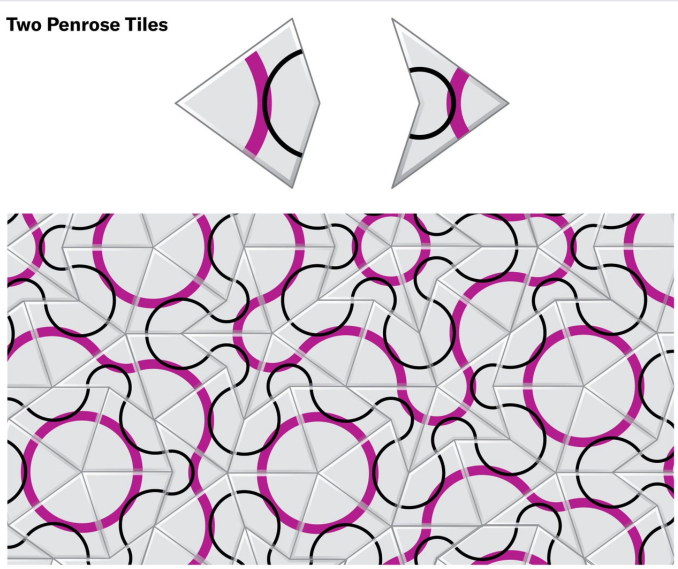
Based on what was known about tilings at the time, Wang's conjecture was quite reasonable. Building on this work a few years later, however, Wang's student Robert Berger disproved the conjecture by constructing the first aperiodic tile set, a sprawling system of 20,426 Wang tiles. In passing, Berger speculated that it should be possible to construct smaller aperiodic sets, inaugurating an irresistible mathematical quest to see how small a set could be.

By 1971 Raphael M. Robinson of the University of California, Berkeley, had gotten down to a set of six modified squares.



Credit: Jen Christiansen

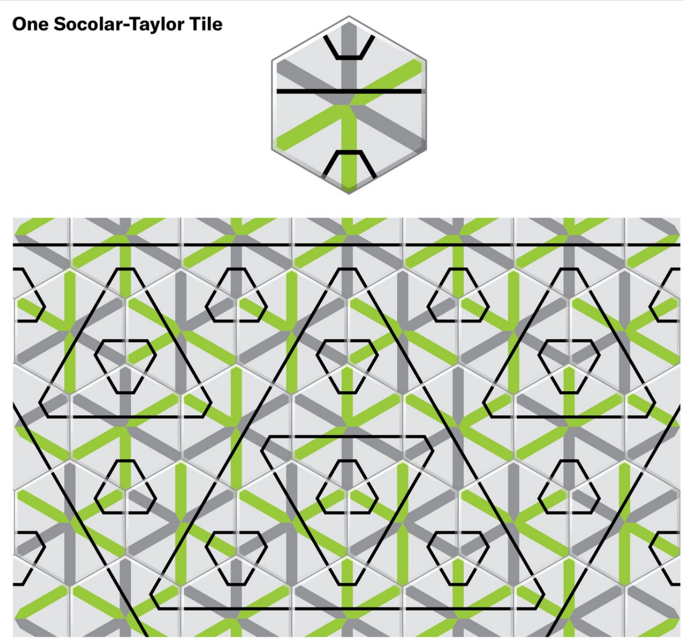
Then, in 1973, University of Oxford mathematician Roger Penrose achieved a stunning breakthrough with a set of just two tiles: the “kite” and the “dart.”



Credit: Jen Christiansen

Penrose's work left us one step short of an obvious finish line: an aperiodic monotile, a single shape that admits only nonperiodic tilings. Such a shape is also sometimes called an “einstein,” from the German “*ein stein,*” meaning “one stone.” (It's a pun on the name “Einstein” but otherwise has no connection to the famous Albert.) The question of whether an aperiodic monotile exists has been called the einstein problem.

After Penrose, progress stalled for nearly 50 years. A few other sets of size two were discovered, including one by Goodman-Strauss. Some mathematicians proposed single-shape solutions, but these inevitably required small amendments to the rules of the game. For example, the Socolar-Taylor tile is a modified regular hexagon that tiles aperiodically. The catch is that for copies of this hexagon to conspire to force all tilings to be aperiodic, nonadjacent tiles must come to an agreement about their relative orientations. There is no way to bake this restriction into the outline of the tile without introducing a trick, such as extruding the hexagon into three dimensions or breaking it into disconnected pieces.

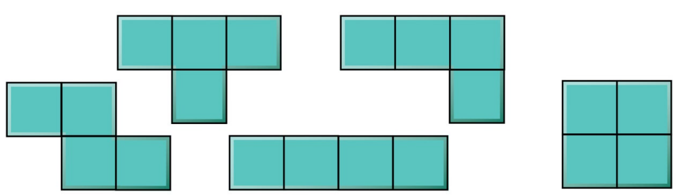


Credit: Jen Christiansen

Even when a problem in mathematics is unsolved, there is often a broad consensus among mathematicians about its likely answer. For example, Goldbach's conjecture states that every even number greater than two is the sum of two odd primes. This conjecture is unproven, but the evidence we have overwhelmingly suggests that it's correct. One reason I was always fascinated by the einstein problem is that I did not see clear evidence for or against it (apart from the grim reality of a 50-year dry spell). Some mathematicians were resigned to the impossibility of aperiodic monotiles, but I was open to either outcome. If nothing else, I suspected that an existence proof would be more tractable than a nonexistence proof. The former was likely to be an argument about the properties of a specific shape, but the latter would necessarily be a statement about all shapes. As we now know, in this instance there is some justice in the universe.

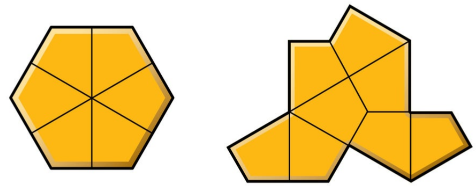
Smith hadn't specifically set out to find an aperiodic monotile, but he was aware of the history and significance of the problem. He was always on the lookout for signs of aperiodicity in his explorations. It was Smith who first dared to suggest, in an e-mail on November 24, 2022, that the hat might be an einstein, modestly adding, “Now wouldn't that be a thing?”

Smith and I began trying to understand the hat's behavior. The hat is what's known as a polyform: a shape made up of copies of some simple unit element. For example, the pieces in the video game *Tetris* represent all the ways to stick four squares together.



Credit: Jen Christiansen

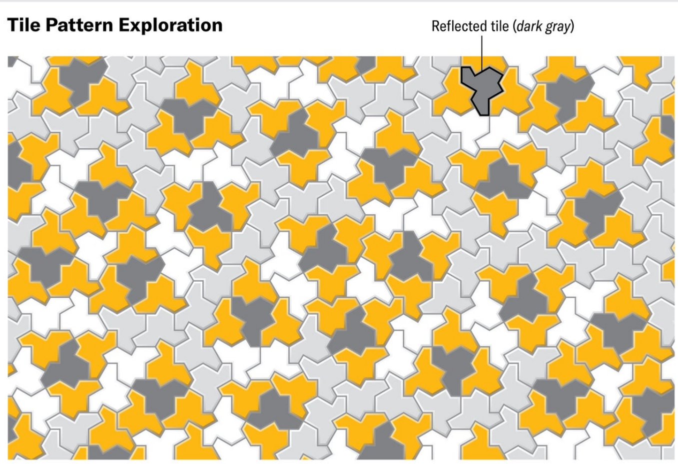
The hat is made from eight kites. These kites aren't the same as Penrose's; Smith made them by slicing a regular hexagon into six equal pieces with lines connecting the midpoints of opposite edges.



Credit: Jen Christiansen

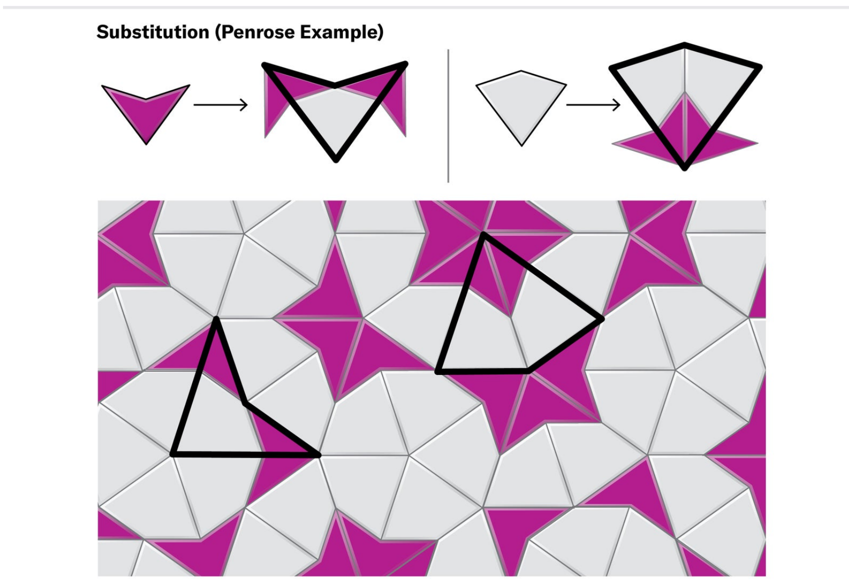
He knew that I had recently written software to compute Heesch numbers of polyominoes (glued-together squares), polyhexes (regular hexagons) and polyiamonds (equilateral triangles), and he wondered whether it could be adapted to polykites. Fortunately, I had added support for kites the year before with the help of Ava Pun, an undergraduate at the University of Waterloo.

My software easily generated large clusters of hats without getting stuck, reinforcing our belief that the hat tiled the plane. Better yet, these new computer-generated clusters became raw data that Smith and I could study to refine our intuition. We began grouping hats in different ways, usually coloring them by hand in digital illustrations, to search for order. Recurring patterns leaped out immediately, organized around a sparse arrangement of reflected hats embedded in a larger field of unreflected hats (something Smith had also observed in his paper experiments).



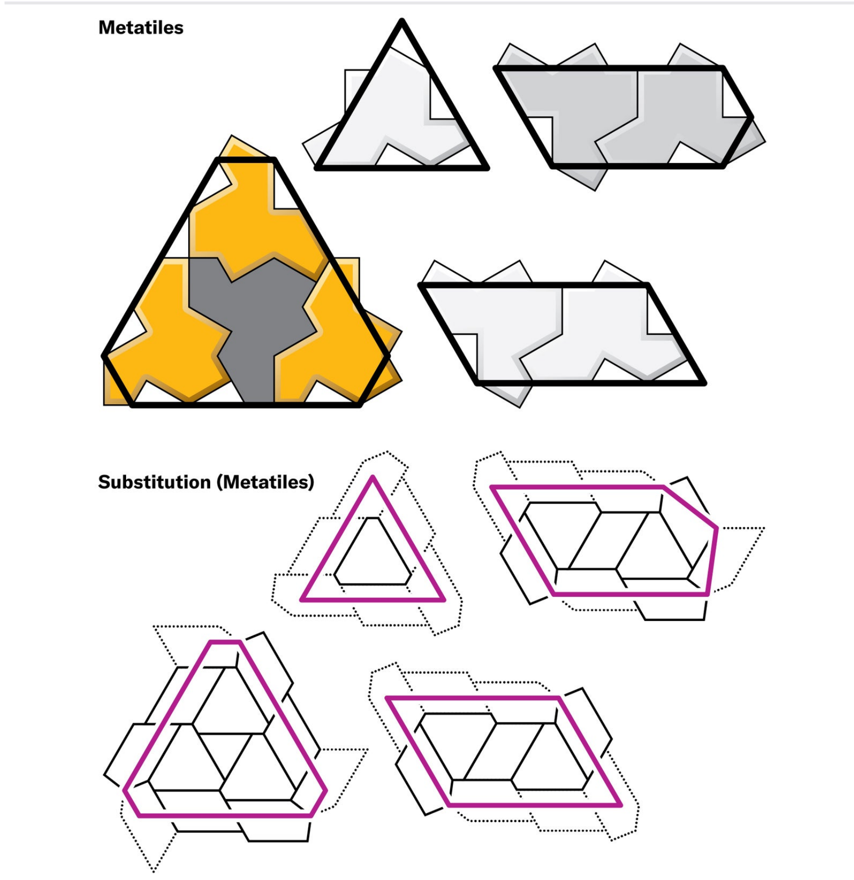
Credit: Jen Christiansen

Yet these patterns never formed a translational unit. Moreover, the tiles seemed to build up into families of related “motifs” at multiple scales. This kind of recurring hierarchy hinted at a best-case scenario for eventually proving the hat was aperiodic: we could hope to find a system of so-called substitution rules. In a substitution system, every tile shape in a set is equipped with a rule that can be applied to replace it by a collection of smaller copies of the tiles. Armed with a suitable substitution system for hats, we might be able to start with a “seed” configuration of tiles and apply the rules iteratively, zooming in as we go to preserve scale. In this way, we would define a sequence of ever-larger clusters of hats, which would eventually fill the entire plane. Many aperiodic tile sets, including Penrose's, can be shown to tile the plane with substitution systems like these.



Credit: Jen Christiansen

On my 50th birthday, about two weeks after I first saw the hat, I found a preliminary set of substitution rules. The trick was to avoid working directly with “naked,” or single, reflected hats, which necessarily behaved differently than their unreflected counterparts. Instead I grouped each reflected hat with three of its neighbors to form an indivisible unit, a new “metatile” that could be treated as a full-fledged tile shape with a substitution rule of its own. I refined the metatiles and their rules through the rest of 2022, arriving at a system of four metatiles, each one a kind of schematic representation of a small cluster of hats.



Credit: Jen Christiansen

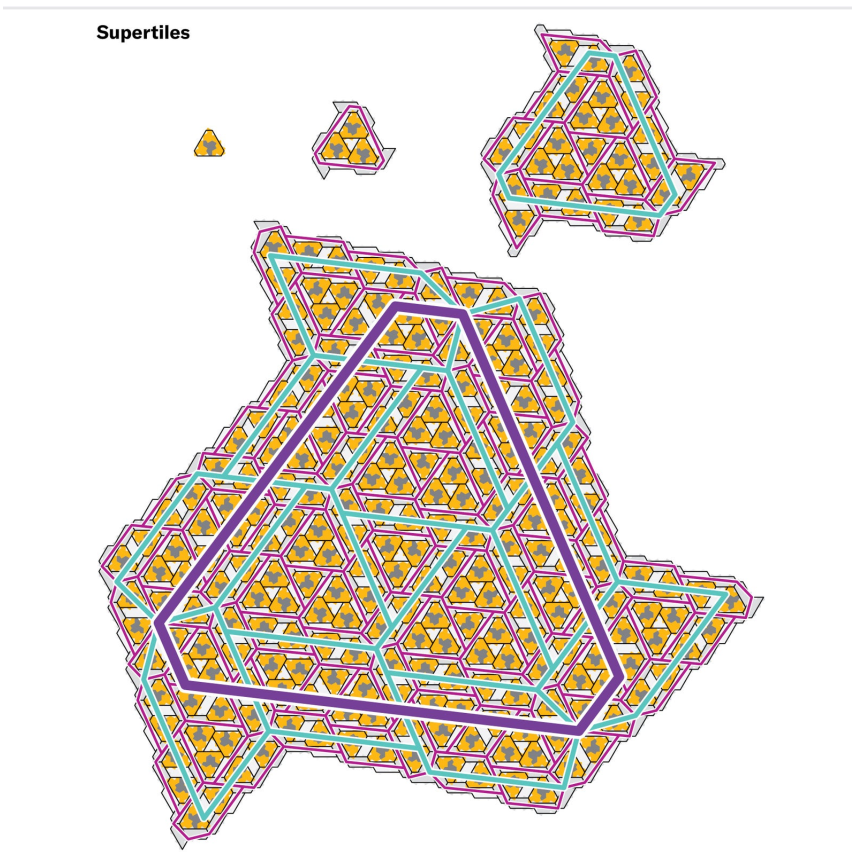
By the start of 2023 Smith and I had half of a proof of aperiodicity, and arguably it was the easy half. Our metatiles and substitution rules guaranteed that the hat was a monotile: it tiled the infinite plane rather than petering out with an unexpectedly large, but finite, Heesch number. And it was easy to see that the tilings generated by the rules were nonperiodic. But remember that nonperiodicity is a far cry from aperiodicity. Perhaps our rules were just an overly complicated way to construct hat tilings, and periodic tilings existed, too. To complete the proof, we had to show that every tiling by hats was necessarily nonperiodic. I had some inkling of how that step might play out, but I felt as I imagine Smith had the previous November: close to the limits of my mathematical expertise. It was time to call in reinforcements.

Early in January 2023 Smith and I reached out to Goodman-Strauss, a mathematician who has published many important articles about tiling theory. I consider him a go-to authority on contemporary research. He is also known as a mathematics communicator and an organizer of hands-on activities, and at the time he was transitioning into a new role as an outreach mathematician at the National Museum of Mathematics in New York City. In other words, he was already swamped. But he provided valuable input and insisted that we also contact Myers immediately. Myers left academia after receiving a Ph.D. in the mathematical field of combinatorics, but he remained interested in tilings. In particular, he maintained a long-term project to catalog the tiling properties of polyforms. I had run some supporting computations for him back in 2006, and I was using his software as part of my own research on Heesch numbers.

I hadn't worked that closely with Myers before, so I was unprepared for his combination of mental horsepower, coding skill and knowledge of the field. His previous work on tilings had left him perfectly prepared for this moment. A mere eight days after being introduced to our work in progress, Myers completed the proof, confirming in late January that the hat was the world's first aperiodic monotile.

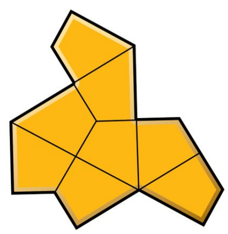
Before Myers came onboard, we already had our substitution rules and could generate tilings; his mission was to prove that all tilings by the hat had to be nonperiodic. In the aperiodicity playbook, the standard move at this point is to show that any tiling bears the imprint of the substitution rules. In other words, he needed to prove that for any arbitrary hat tiling, there is a unique way to group tiles into metatiles, metatiles into supertiles, and so on forever, reverse-engineering an infinite tower of substitutions that ends with the full, infinite tiling. A preexisting mathematical argument then would allow us to conclude that the tiling must be nonperiodic. The challenge of this strategy is to locate this tower atop an arbitrary hat tiling whose construction was not constrained at the outset to obey our rules.

Myers developed a computer-assisted approach to solving this problem. We generated an exhaustive list of 188 small clusters of tiles that could appear in hat tilings. These clusters represented every legal arrangement around a single hat so that each tile in any conceivable tiling must lie at the center of one such cluster. Myers then showed that each of these clusters could be divided up in a unique way into fragments of the metatiles, implying that the hats in any tiling could be grouped to yield a tiling by metatiles. Finally, he demonstrated that in a tiling made of metatiles, it was always possible to group metatiles into larger clusters called supertiles, which behave exactly like larger metatiles. This last step launches a kind of recursion: because the supertiles behave just like metatiles, the same grouping process applies to them as well. Once we group hats into metatiles and metatiles into supertiles, all subsequent levels of the hierarchy lock into place with a single mathematical flourish.



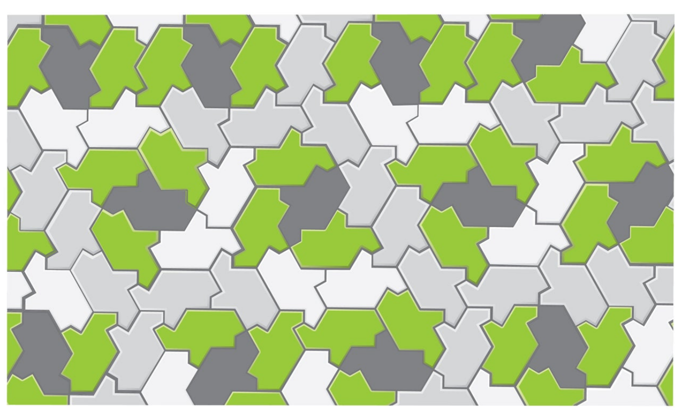
Credit: Jen Christiansen

We had our prize, and in early February 2023 we began writing a manuscript to share the hat with the world. That might have been the end to an already magical story were it not for Smith's capacity for mathematical discovery. Way back in December 2022 he had shocked me by e-mailing me a second shape, a polykite we call the turtle, which behaved a lot like the hat. The turtle, too, radiated an uncanny aura of aperiodicity. Was it possible that Smith had discovered two revolutionary shapes in two weeks after others had looked in vain for 50 years? I begged for patience; my head was already full of hats, so to speak.



Credit: Jen Christiansen

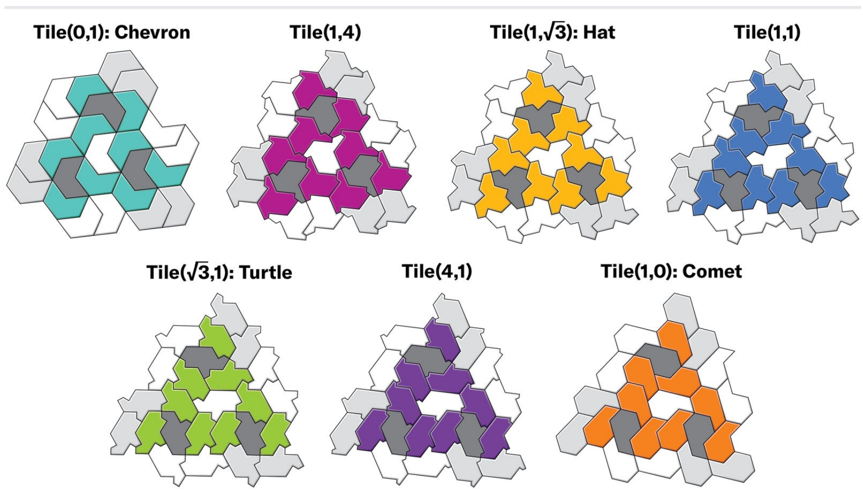
But after resolving the status of the hat, Myers began contemplating the neglected turtle. A week or two later he stunned the three of us with the observation that the turtle was necessarily also aperiodic because it was really just a hat in disguise. In fact, the hat and the turtle were two shapes in a continuous family of polygons, all of which were aperiodic and tiled in the same way.



Credit: Jen Christiansen

The hat can be regarded as a polygon with edges of length 1 and √3 (where two consecutive edges of length 1 form one longer edge).

Just as one can construct a family of rectangles by varying the lengths of its horizontal and vertical edges independently, we can choose any two numbers *a* and *b* to replace the hat's edge lengths and obtain a new polygon that we will call Tile(*a*,*b*). Using this notation, the hat is Tile(1,√3), and the turtle is Tile(√3 ,1). Myers showed that nearly all shapes of the form Tile(*a*,*b*) are aperiodic monotiles with the same tilings. There were just three exceptions: Tile(0,1) (the “chevron”), Tile(1,0) (the “comet”) and the equilateral polygon Tile(1,1) (which never acquired a catchy nickname). Each of these three shapes is more flexible, admitting both periodic and nonperiodic tilings.



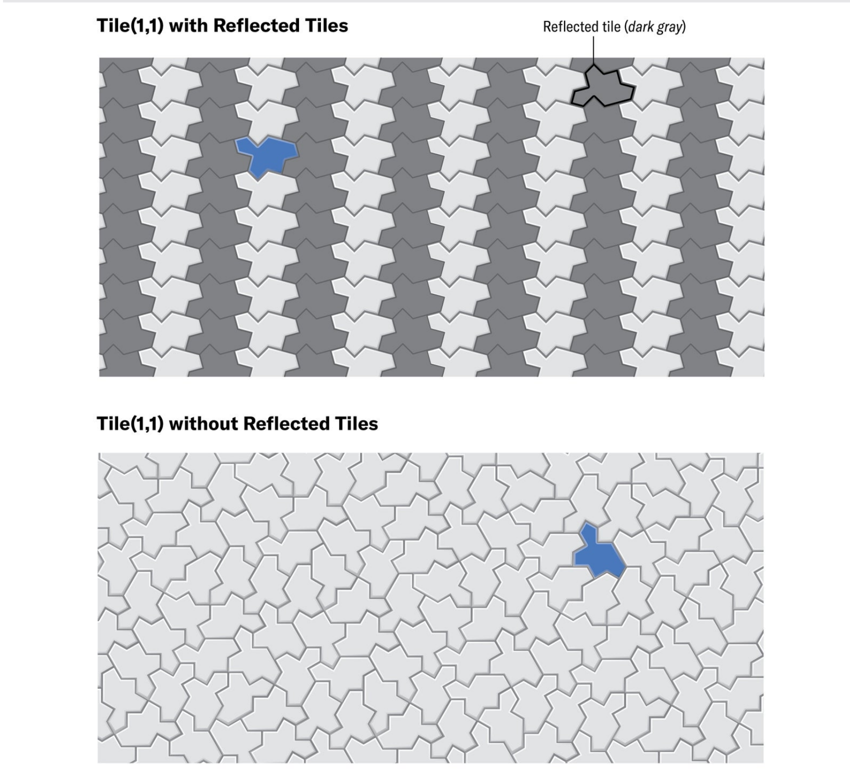
Credit: Jen Christiansen

Soon after, Myers doubled down on the link he had forged between the hat and the turtle, developing a remarkable second proof of the hat's aperiodicity based on the Tile(*a*,*b*) continuum. He relied on the classic technique of proof by contradiction: he posited the existence of a periodic tiling of hats, and then, from the existence of such a tiling, he derived an absurdity that showed the initial supposition (the periodic hat tiling) was impossible. Specifically, he found that one could stretch and squeeze edges in a periodic hat tiling to obtain equivalent, periodic tilings by chevrons and comets. But chevrons and comets are both polyiamonds (unions of equilateral triangles) built on top of regular triangular tilings at different scales. In an argument that involves combinatorics, geometry and a dash of number theory, Myers proved that because the chevron and comet tilings originated from the same supposedly periodic hat tiling, their underlying triangle tilings would have to be related to each other through a mathematically impossible scaling factor. This was a second way to prove that the hat is an aperiodic monotile. It's exciting not just because it bolsters the claim of the hat's aperiodicity but also because it represents a whole new method of proof in this field, which could be useful in analyzing other tiles in the future.

We put our manuscript online in March 2023 and received an enthusiastic, overwhelming response from mathematicians and tiling hobbyists. The hat became an immediate source of inspiration for artists, designers and puzzle creators (you can now buy hat tiling sets on Etsy, for instance). It's important to remember that the work has not yet emerged from the crucible of peer review, although it has withstood a great deal of scrutiny from experts with barely a scratch.

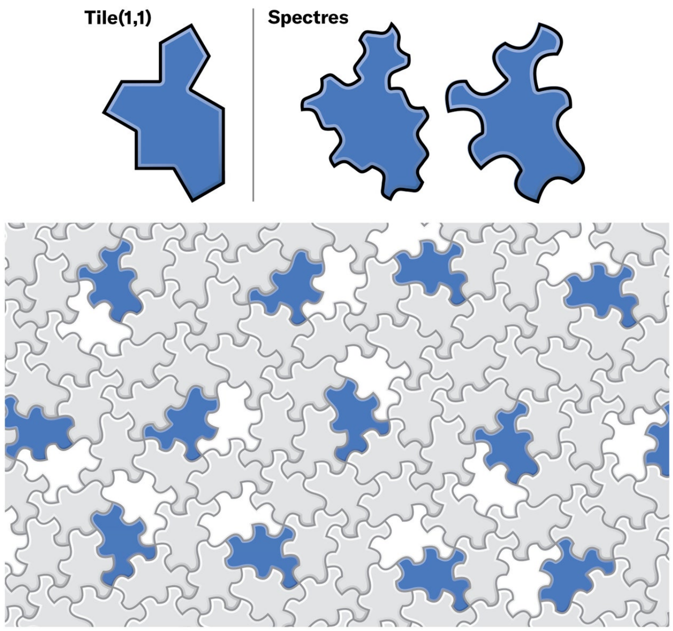
When we first revealed the hat, people objected to one aspect of our work more frequently than any other: the use of reflected tiles. Every tiling by hats must include a sparse distribution of reflected hats, as Smith and I discovered early on. Mathematically, this objection does not derail our result: the accepted definition of a monotile has always allowed reflections as legal moves in tilings. Still, many wondered, could there be a shape out there that yields a “one-handed,” or “chiral,” aperiodic tiling in which no tiles are flipped over? Our manuscript offered no insight into this problem, and we were as prepared as everyone else to settle in for the long wait until its resolution.

Happily, Smith had one more astounding surprise for us. Less than a week after our first manuscript went live, he began e-mailing the rest of us about Tile(1,1), the equilateral member of the continuum of shapes that included the hat and the turtle. We knew that this polygon was not aperiodic: it admitted periodic tilings that mixed unreflected and reflected tiles. But Smith observed that if he deliberately restricted himself to tiles of a single-handedness (no flipping allowed), he produced intriguing clusters of tiles.



Credit: Jen Christiansen

The four of us immediately dove into a new collaboration. We computed large patches of unreflected copies of Tile(1,1) and studied them for patterns. We discovered a way to group tiles into recurring clusters and then determined substitution rules for those clusters that yielded superclusters with identical behavior. Once again, this recursive grouping guaranteed the existence of a unique infinite hierarchy of substitutions that forced all unreflected (single-handed) tilings to be nonperiodic. The final trick was simply to replace the edges of Tile(1,1) with arbitrary curves, which guaranteed that tiles and their reflections couldn't coexist in a tiling. The result was a family of shapes that we called spectres, all of which turned out to be chiral aperiodic monotiles.



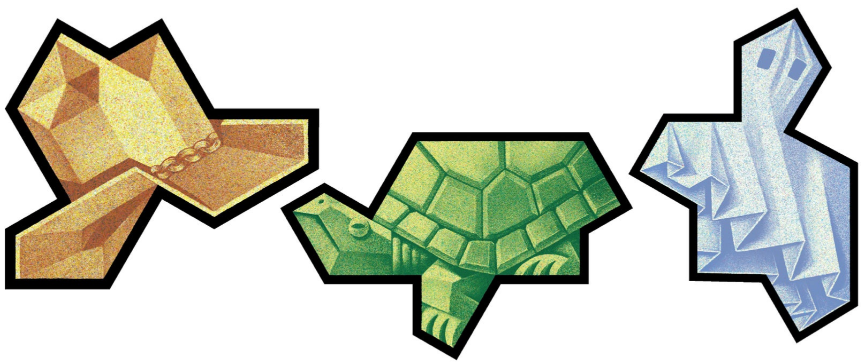
Credit: Jen Christiansen

There is a romance to stories of mathematicians working for years on intractable problems, sometimes in secret, and finally emerging into the light with a new result. That is not our story. Although I was always fascinated by the einstein problem, I never worked on it directly—I started only when I was handed the answer in November 2022. The hat more or less materialized in Smith's hands, and I was lucky that he chose to contact me. A few months later we had a complete proof, created through a process that was, as far as I can tell, painless for all four of us. Perhaps our pace reflects the fact that there is a clear procedure to follow in generating a proof of aperiodicity if you have the right shape to begin with. Our sense of ease was also surely a result of the decades we had each spent pondering the einstein problem and related questions. That experience left us well positioned to recognize the hat as a possible solution and to know what to do with it.

There is no shortage of unsolved problems in tiling theory, a branch of mathematics with a low barrier to entry and lots of visual appeal. Smith joins a pantheon of enthusiastic amateurs who have made important contributions to the field, often after reading about open problems in this magazine. He is in the company of Robert

Ammann, who independently discovered many of the same results as Penrose and contributed other important ideas to tiling theory; Marjorie Rice, who discovered new classes of pentagonal monotiles; and Joan Taylor, who originated the Socolar-Taylor tile. I should also include the artist M. C. Escher, who invented the math he needed to draw his tessellations, even if he would not have thought of it as math at all.

As the impact of our aperiodic monotiles ripples outward, I'm sure it will stimulate new scholarly research. But I hope we also entice others who might have seen mathematics as forbidding but now recognize an opportunity to play.



Credit: Miriam Martincic

Craig S. Kaplan is a professor of computer science at the University of Waterloo in Canada. His research focuses on interactions between mathematics and art, and he has long had an interest in mathematical tiling.

Asexuality Is Finally Breaking Free from Medical Stigma

New research on asexuality shows why it's so important for doctors and therapists to distinguish between episodes of low libido and a consistent lack of sexual attraction

By Allison Parshall

Marcos Chin

In graduate school people often asked Megan Carroll whether she was gay. Her sociology dissertation was on inequalities within communities of gay fathers, so her research participants were curious about how she identified. "I would say, 'Oh, I'm maybe mostly straight? I don't really know. It's complicated.'" It was, at the time, the closest she could get to the truth. She'd had crushes on both boys and girls in high school and had been in a relationship with a man; being around her romantic interests sent her heart fluttering in her chest. But nothing like that happened when she considered having sex with any of them—she simply wasn't interested. Her friends assured her she just needed to meet the right person, someone who would light her fire.

When that hadn't happened by the time she was 18, Carroll thought she might simply have a low libido and went looking for an explanation. Thinking her birth control might be to blame, she spoke with a nurse, who suggested that perhaps her boyfriend was “just a bad lover.” Then Carroll wondered whether it was the pills she was taking to treat her depression. Over the next 12 years she visited multiple therapists, psychiatrists and physicians and tried different antidepressants—including a less commonly prescribed drug that gave her tachycardia, or a faster heart rate. Eventually she settled on one that had shown no measurable effect on sex drive in clinical trials.

Throughout these years of experimentation, Carroll's libido—the physiological desire for sexual stimulation and release—did fluctuate. But what remained constant was that her libido was rarely, if ever, directed at another person, even her crushes.

In 2016 Carroll stumbled on a Facebook post about asexuality. She'd heard the term, typically defined as experiencing little to no sexual attraction, but had never felt that it applied to her. Then Carroll read a comment that mentioned demisexuality, a specific experience of feeling sexual attraction only after developing an emotional bond with someone. The idea that asexuality was a spectrum opened an entire world that had never been discussed in her gender and sexuality courses—one in which sexual desire was not necessary for a fulfilling life.

Because this idea subverts a cultural assumption about what it means to be human, it is often difficult for asexual people to recognize, let alone embrace, their identity. “Your very existence is, in some way, in opposition” to the societal norm, says CJ Chasin, an asexual gender and sexuality scholar at the University of Windsor in Canada. Even after realizing she probably was asexual, Carroll still visited doctors to experiment with her medications before finally accepting that she just is the way she is.

Over the past two decades psychological studies have shown that asexuality should be classified not as a disorder but as a stable sexual orientation akin to homosexuality or heterosexuality. Both cultural awareness and clinical medicine have been slow to catch on. It's only recently that academic researchers have begun to look at asexuality not as an indicator of health problems but as a legitimate, underexplored way of being human.

In biology, the word “asexual” typically gets used in reference to species that reproduce without sex, such as bacteria and aphids. But in some species that do require mating to have offspring, such as sheep and rodents, scientists have observed individuals that don't appear driven to engage in the act.

This behavior is more analogous to human asexuality, a concept rarely mentioned in medical literature until recently. In a pamphlet published in 1896, pioneering German sexologist Magnus Hirschfeld described people without sexual desire, a state he called “anesthesia sexualis.” In 1907 Reverend Carl Schlegel, an early gay rights activist, advocated for the “same laws” for “the homosexuals, heterosexuals, bisexuals [and] asexuals.” When sexologist Alfred Kinsey devised his scale of sexual orientation in the 1940s, he created a “Category X” for the respondents who unexpectedly reported no sociosexual contacts or reactions—exceptions from his model whom he estimated made up 1.5 percent of all males between the ages of 16 and 55 in the U.S. Asexuality was largely absent from scientific research over the subsequent decades, although it was occasionally referenced by activists and scholars in the gay liberation movement.

It wasn't until the World Wide Web emerged that asexual people around the globe began finding one another on Internet forums. They started building a shared language in the early 2000s, mapping the landscape of asexuality through a grassroots development of concepts and labels. Calling themselves “aces,” they tended to split sexual and romantic attraction into spectrums of their own; asexual people can experience varying levels of each. Aces can be sex-repulsed, sex-neutral or sex-favorable; they may have sex frequently or never.* There are aces who have high libidos and aces with none to speak of. Some aces masturbate, and others don't. Different as they are, members of the ace community are unified by their relative lack of sexual, and sometimes romantic, attraction to others.

At the time, however, being asexual could be considered indicative of a psychiatric disorder, according to the American Psychiatric Association's *Diagnostic and Statistical Manual of Mental Disorders* (*DSM*). If someone reported being distressed by their low sexual desire, a doctor could diagnose them with hypoactive sexual desire disorder (HSDD). A person could also qualify for the diagnosis if their partner was upset by their low sexual desire—even if they themselves were fine with it. In other words, the person in a couple “who didn't like sex enough had the disorder,” explains David Jay, founder of the Asexual Visibility and Education Network (AVEN), an online forum that became a starting point for much of the ace community.


Credit: Marcos Chin

Levels of sexual desire can fluctuate throughout life for many reasons that may or may not be a cause for medical concern, including changes to hormone levels or mental health. If someone is experiencing significant distress about a dip in desire, they may benefit from diagnosis and treatment. But asexual people tend to experience their lack of sexual attraction to others as a relatively stable orientation rather than a disorder requiring intervention. So when work began on an updated version of the *DSM* in the late 2000s, Jay and others at AVEN wanted to make this clear to the scientists drafting it. “We wanted researchers to, at the very least, understand how we think about ourselves before they interpret data about us,” Jay says. The AVEN team conducted a review of the literature and interviewed seven researchers, most of them psychologists.

AVEN put its findings in a report and sent it to the committee in charge of reevaluating the HSDD diagnostic criteria for the *DSM*'s fifth version. One committee member was Lori Brotto, a psychologist at the University of British Columbia who was conducting some of the earliest studies of asexuality. Brotto found that AVEN's report aligned well with what she was already learning from her research, which compared the behavior, experiences and physiological responses of self-identifying asexual people with those of nonasexual people who had received an HSDD diagnosis. She consistently found differences in responses among the asexual group that suggested asexuality shouldn't be categorized as a sexual dysfunction.

In 2013 the *DSM-5* was published with a revamped section on sexual dysfunction that split HSDD into male and female disorders with new names. Each one contained a line specifying that someone who identifies as asexual should not be given the diagnosis. This change meant that asexuality was no longer a disorder in the eyes of the American Psychiatric Association, and it opened up new ideas for researchers investigating sexual desire.

The study of asexuality developed throughout the mid-2010s and is now growing rapidly, says Jessica Hille, a gender and sexuality researcher at Indiana University's Kinsey Institute. In a review published in November 2022, Hille found 28 studies on asexuality published between January 2020 and July 2022, “whereas 10 years ago I don't know that you would have found 28 papers in the [entire] field,” she says.

Today “asexuality is widely accepted as a sexual orientation in the literature,” Hille says, but cultural awareness remains in its infancy, especially compared with other orientations under the LGBTQIA+ umbrella. Saying you don't experience sexual attraction is still like saying you don't eat, Hille explains, and “if you don't eat, there's something wrong with you, and you're hurting yourself.” Asexual people sometimes get this message not just from family and acquaintances but from their health-care providers.

Shelby Wren, a health equity researcher at the University of Minnesota, published a study in 2020 in which 30 to 50 percent of respondents who had disclosed their asexuality in a medical setting said a therapist or doctor had attributed their asexuality to a health condition. The proposed diagnoses included anxiety, depression and, in one case, a personality disorder. “You don't know what's going to happen when you disclose your sexual orientation," Wren says. "And for a lot of people, that stops them from talking about things that could be relevant to their health care."

For Rowan, an actor and writer based in Scotland, who asked to be identified by first name only, this very experience began with a routine appointment with their gynecologist. When the nurse asked whether they were sexually active, they said no—they had a boyfriend but hadn't had penetrative sex. "I don't want to," Rowan recalls explaining to the nurse. "I don't feel anything. I don't feel ready enough." Rowan, who was in their early 20s at the time, felt ashamed, "like there was part of me that wasn't right, and I wanted it to be fixed." The doctor referred Rowan to a psychosexual therapist. In their first therapy appointment, Rowan suggested that they might not be sexually attracted to anyone. They don't recall the therapist mentioning that again over the course of four appointments; instead the therapist suggested a physical exam of Rowan's genitals.

During the internal exam, Rowan felt "nothing" and removed from their body. "That was really confusing for me at the time, that a medical exam is just as cold and devoid of any feeling" as was physical intimacy with their boyfriend. Rowan recalls the therapist reporting that nothing was physically wrong with them and then spending the next few sessions trying to identify Rowan's mental blockage. These encounters had lasting effects on Rowan, including dissuading them from seeking therapy to treat their depression.

Rowan is not alone. In a report on asexual discrimination published in October 2023 by Stonewall, a U.K.-based LGBTQIA+ rights organization, many interviewees reported that low awareness of asexuality had negatively impacted their health care at some point. One participant's therapist told her to set goals to get over her "fear of sex" and to take a medication to increase her libido. Another participant's therapist assumed that her asexuality stemmed from childhood trauma and would change with time, which led the participant to force herself to do things she was not comfortable with. And another participant's doctor assumed her asexuality came from her antidepressants. (While antidepressants have been shown to impact one's physiological desire for sexual release, or libido, there is no evidence that they lower one's sexual attraction to others, which is the component of desire that is most relevant to asexuality, Carroll explains. Some asexual people have never taken these medications, including sources quoted in this article.)

Other stories in the report show what can happen when asexuality becomes the focus of doctor's visits for completely unrelated issues, interfering with treatment and even causing harm. This was an “overwhelming pattern” in the report, says lead author and asexual activist Yasmin Benoit. One participant who was suffering from pelvic pain, for example, described how her general practitioner would not give her a referral to a gynecologist until she first saw a psychosexual therapist. This prerequisite resulted in a seven-month delay in treatment and, according to the participant, “extensive muscular damage.”

Refraining from disclosing one's asexuality to a mental health provider is often a “very rational decision,” Chasin says. “It's always much worse to be actively rejected and misunderstood.” For instance, asexual people are sometimes subjected to conversion therapy, a practice aimed at changing someone's sexuality or gender identity. It is banned for minors in 22 U.S. states because of its well-documented and extensive harms, including increased rates of suicide. A 2018 U.K. government survey of LGBTQIA+ people found that asexual respondents were the most likely to be offered conversion therapy and as likely as gay and lesbian people to receive it. A recent survey by the Trevor Project found that 4 percent of asexual youths in the U.S. were subjected to conversion therapy, on par with bisexual respondents.

On the legislative level, bans on conversion therapy should explicitly reference asexuality, Benoit says. So, too, should professional associations of health-care practitioners, says Samantha Guz, a social work researcher at the University of Chicago. “Asexual people are made to be so invisible in our society that I don't think just having a broad call against conversion therapy is specific enough,” Guz says.

Even well-meaning doctors might unwittingly harm their patients. To a clinician, a patient who is worried that they *should* feel more sexual desire—and who does not know they are simply asexual—might initially look similar to patients who want sexual intimacy and could benefit from treatments aimed at increasing or restoring desire. Treatments for certain types of sexual dysfunction do help some people whose level of sexual desire leaves them distressed and unsatisfied, Brotto says. For some people, though, this distress may be coming not from an intrinsic desire to want sex but from external pressures such as partners or society as a whole. “I have worked with folks where it's taken us many, many months for the person to really understand how well asexuality fits with their identity,” as opposed to having an issue that is rooted in a health problem or a situational condition, Brotto says. Most doctors, though, don't know that such a distinction exists or is necessary, she adds.

Since coming to embrace their asexuality, Rowan has become more comfortable with expressing love and receiving it from friends and partners without the weighted expectations of sex. With their most recent therapist, they finally had a positive experience talking about asexuality in therapy. “She would ask me specific questions about [my asexuality], but she didn't make assumptions about what it meant,” Rowan says.

In early 2022 the American Association of Sexuality Educators, Counselors and Therapists published a position statement on how to care for asexual patients. It says asexuality is not a disorder or a response to trauma and that asexual individuals often face difficulty in finding affirming health care. (Unlike the *DSM*, the World Health Organization's International Classification of Diseases still hasn't specified that asexuality isn't a disorder.) The association opposes “any and all” attempts to change or pathologize someone's asexual orientation and labels such attempts as conversion therapy.

Jared Boot-Haury, a clinical psychologist and certified sex therapist, who drafted the statement, hopes that larger organizations such as the American Medical Association will put forward similar statements and, ultimately, clear and empirically supported guidelines for clinicians.

Meanwhile many studies of asexuality are moving beyond confirming it exists, instead exploring how ace people find intimacy in their relationships and personal fulfillment outside of the cultural scripts for building a life around a sexual or romantic partner. The asexual community has had to reimagine love and relationships to fit its needs; this wisdom could help everyone, asexual or not, Jay says. He cites the U.S. surgeon general's recent report of an “epidemic” of loneliness, which showed how social connection has significantly decreased over the past 20 years.

“Because the ace community was denied the infrastructure of intimacy and had to invent our own, we have become this site of innovation that a lot of people, especially nonqueer people, suddenly are interested in,” Jay says. He is raising a child in a three-parent family, which was the subject of a 2020 *Atlantic* article. Jay now counsels people, asexual or otherwise, on how to build intentional relationships outside of cultural norms.

Carroll, now a sociologist at California State University, San Bernardino, also investigates resources for ace people that might apply more broadly. Some of her latest work examines the difficulty that asexual and aromantic people often face in accessing middle-class housing systems, which are built for nuclear family structures that might not be attainable or desirable for many asexual people, she explains.

Having found a home in the ace community both personally and professionally, Carroll now understands the distress that drove her to doctors' offices quite differently. She must have known “deep down inside” that her disinterest in sex wasn't a problem; it's “the rest of the world that's a problem,” she says. Today her students seem so “receptive to asexuality, wanting to learn about what I know.”

It's not just young people who are coming around. When Carroll lectures about asexuality, she often tells a story about her mother, Laura Vogel, a licensed professional counselor who specializes in recovery from sexual trauma. Vogel knew traumatic experiences could decrease someone's desire for sex, but for a long time she didn't know that asexuality could be something entirely separate from that. When Carroll came out as asexual to her mother in 2017, Vogel began reading up on the subject and realized how her lack of awareness might have affected her clients. “That was a learning period for me,” Vogel told me recently. Since then, if a client expresses little to no desire to have sex, she sends them home with resources about asexuality to see whether it resonates.

“If a therapist had done what my mom now does ... it's hard to describe what that would have meant for me personally,” Carroll says. “That awareness can save asexual people years and years of uncertainty.”

**Editor’s Note (1/5/24): This sentence was edited after posting to replace the term “sex-positive” with “sex-favorable,” which is preferred by many in the asexual community.*

Allison Parshall is an associate news editor at *Scientific American* who often covers biology, health, technology and physics. She edits the magazine's Contributors column and weekly online Science Quizzes. As a multimedia journalist, Parshall contributes to *Scientific American*'s podcast *Science Quickly*. Her work includes a three-part miniseries on music-making artificial intelligence. Her work has also appeared in *Quanta Magazine* and Inverse. Parshall graduated from New York University's

Arthur L. Carter Journalism Institute with a master's degree in science, health and environmental reporting. She has a bachelor's degree in psychology from Georgetown University. Follow Parshall on X (formerly Twitter) @parshallison

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Animals

- ## Rising Temperatures Are Turning Some Animals Nocturnal
  As climate change makes the planet hotter, some animals might become more active at night to escape the midday heat
- ## Cats Are Perfect. An Evolutionary Biologist Explains Why
  Cats have attained evolutionary perfection

Rising Temperatures Are Turning Some Animals Nocturnal

As climate change makes the planet hotter, some animals might become more active at night to escape the midday heat

By Ethan Freedman

A collared peccary, close relative of the white-lipped peccary.
gerard lacz/Alamy Stock Photo

The white-lipped peccary, a piglike animal native to Central and South America, usually forages for fruit and other plants during the day and sleeps at night. But scientists in Brazil's Pantanal wetlands have found that when it gets unusually hot, these animals become more nocturnal. This behavioral flexibility could help peccaries—and potentially other species—adapt to climate change. “Maybe there's hope for species to be resilient, to an extent,” says Michaela Peterson, a doctoral candidate at Vanderbilt University and coauthor of a recent study published in *Biotropica*. The study found that during relatively balmy periods, when daily high temperatures were lower than 80 degrees Fahrenheit on average, white-lipped peccaries were most active in the afternoon. In slightly hotter weather they shifted their activity to the morning. But once average daily highs topped 94 degrees F, peccaries were most active after sunset.

Studies have found similar shifts in other species, including giant anteaters and cheetahs. But even though becoming more nocturnal seems like an obvious way to beat the heat, the potential impact of climate change on the timing of animal activity has not been widely studied, says Michiel Veldhuis, an ecologist at Leiden University in the Netherlands, who was not involved in the new research.

These studies looked at how shorter-term temperature fluctuations changed the animals' behavior, and it's not certain that any species will become permanently more nocturnal because of climate changes in the long term. Embracing the night life could come with significant trade-offs: Nocturnal predators such as pumas often hunt peccaries and anteaters, and Veldhuis says he would like to test whether predation kills more peccaries during the hottest months of the year. Animals used to the daylight also might have trouble spotting their own food if they make the switch, says postdoctoral ecologist Kwasi Wrensford of the University of British Columbia, who was not involved in the new research.

Plus, animals that are usually active during the day might try to avoid nocturnal activity when possible. Peterson says the fact that the peccaries shifted their activity to the morning first—when it's cooler, but there is more light than at night—may indicate that the animals still prefer to be active during the day and become creatures of the night only when temperatures turn truly sweltering.

Ethan Freedman is a science and nature journalist based in New York City who reports on climate, ecology, the future and the built environment.

Cats Are Perfect. An Evolutionary Biologist Explains Why

Cats have attained evolutionary perfection

By Kate Wong

Shideh Ghandeharizadeh

Anjali Goswami thinks cats are perfect—not in the same way as the average cat person, out of admiration for their beauty, athleticism and independence of spirit, but from a scientific standpoint. Goswami is an evolutionary biologist at the Natural History Museum in London who studies large-scale patterns of evolution in vertebrate animals over time. She contends that cats—from tabbies to tigers—are quintessential products of evolution. Her explanation reveals cats, and the meaning of evolutionary success, in a fascinating new light.

An edited transcript of the interview follows.

When I first came across your argument about cats being perfect, my initial thought as a cat fan was, "Well, of course

they are. Science confirms the obvious." But then I realized that this was a really interesting idea. How did it come about?

I was reading a book by Alex Dehgan called *The Snow Leopard Project*. In it, Dehgan mentions that in this area in Afghanistan where he was setting up a national park, there are several cat species. I thought that was kind of amazing because ecologically cats all do the same thing. They're hard-core predators. They're carnivores. And there are lots of other places around the world where multiple species of cats have been able to coexist—not only today but also in deep time. The thing is, although there are lots of species, they all kind of look the same. They're just big or small. I started thinking about how cats can be so similar.

Tell me more about how they are similar. I'm thinking of all the breeds of domestic cats, and even within just that species, there seems to be a lot of variation.

They have different coat colors, sure. But they all have the same baby heads—they're round, and they don't elongate as the animal matures, which goes against the standard developmental pattern for mammals. Dogs have short, round faces as puppies but long, snouty faces as adults. An adult cat looks pretty much like a baby cat but bigger. With dogs, breeders play off that developmental variation to create breeds with different face shapes. But because cats don't have that developmental variation, there isn't much to play around with other than coat color.

This all goes back to the fact that cats are extremely specialized. Every member of the order of mammals known as the carnivorans, which includes cats and dogs, has an upper fourth premolar and a lower first molar that form what we call the slicing pair, which slices meat. Many carnivorans retain molars behind the slicing pair that can grind up stuff such as vegetation. But cats have lost pretty much everything behind their slicing teeth. They might have a nub, a peg tooth, but it can't process stuff. This difference is why foxes are perfectly happy going through garbage, whereas leopards will kill livestock instead.

It doesn't matter whether they're tiny Bengal cats or gigantic lions or tigers; they're gonna basically look the same. If you handed me a lion or tiger skull, I could not—as a person who's a pretty solid expert in carnivorans in general—tell you which one it was. Most people would be hard-pressed to tell you. They look nearly identical. That's how similar cats are. There's a teeny amount of allometry [disproportionate change in one body part relative to the whole as a consequence of size] if they get really big: a small elongation of the face and an increase in muscle mass. But the variation is nothing compared with what you see in other groups such as dogs. Ultimately big cats are really similar to small cats, far more so than you would predict.

What does this have to do with being perfect?

Cats have nailed one thing so well that they all do it and just come up with slightly different sizes. That's why they're perfect evolutionarily. They don't need variation. They might get bigger or smaller, but they don't change anything else, because they're just right otherwise. They're not jacks-of-all-trades; they're masters of one.

Bears are the anticats. There are only a few species of bear, and they do different things. You've got your superspecialized, weird herbivore, the giant panda, which basically eats only bamboo. And then you've got spectacled bears, which favor fruits and bromeliads. You've got polar bears, which are hypercarnivorous marine mammals, and the omnivorous black bears and grizzlies. And then there are sloth bears, which mostly eat social insects. So almost every single species of bear does something totally different. And they're just okay at all of it [laughs]. I really do like bears a lot because of that opposite side of things. They're interesting because they're so ecologically diverse.

People usually talk about a group's diversity as a mark of success. But you're saying it's the sameness of cat species, their lack of variation, that indicates that they're evolutionarily successful or "perfect."

Cats challenge standard biases in evolutionary biology. People have said to me, "What about bats? What about rodents? These groups have so many species doing all kinds of things." And I'm like, "Yeah, because they suck." They haven't figured out how to do anything well, so they keep trying different things.

Do any other vertebrate groups measure up to cats in this way?

Monitor lizards are as awesome as cats. They are the cats of the reptile world. They vary hugely in body size—they have maybe an even bigger body-size range than cats do—and they are all utterly identical. They're also hard-core carnivores.

You and your colleagues have been studying skull evolution. Did you discover anything interesting about cats in the course of that research?

We've been trying to measure skull shape in a similar way across all tetrapods [vertebrates with four limbs]. We're looking at salamanders and frogs, birds and crocodiles, dinosaurs and mammals, and then we try to understand what we see—the variation, the speed at which things evolve and the factors that are associated with how fast things evolve. Within mammals specifically, being social or solitary affects how fast you evolve. Social mammals evolve faster. Cats are notoriously solitary except for lions. And cats don't evolve quickly. Compared with other groups, cats are slowly evolving animals.

There are lots of things that have tried to be cats—other groups of mammals that have evolutionarily converged on cats. Marsupials have tried to be cats. An extinct group of carnivorans called creodonts tried to be cats. Weasels have tried to be cats. There's all kinds of stuff that has tried to be a bit catlike in different ways. But they kind of dip in and dip out of being cats, and they can't really outcompete cats in their space. They haven't lasted. All of those things that have tried to be cats do other things, too, and those things are fine. But there aren't a lot of things that are around today that do a very good job of being a cat.

Kate Wong is an award-winning science writer and senior editor at *Scientific American* focused on evolution, ecology, anthropology, archaeology, paleontology and animal behavior. She is fascinated by human origins, which she has covered for more than 25 years. Recently she has become obsessed with birds. Her reporting has taken her to caves in France and Croatia that Neandertals once called home, to the shores of Kenya's Lake Turkana in search of the oldest stone tools in the world, to Madagascar on an expedition to unearth ancient mammals and dinosaurs, to the icy waters of Antarctica, where humpback whales feast on krill, and on a "Big Day" race around the state of Connecticut to find as many bird species as possible in 24 hours. Kate is co-author, with Donald Johanson, of *Lucy's Legacy: The Quest for Human Origins*. She holds a bachelor of science degree in biological anthropology and zoology from the University of Michigan. Follow Wong on X (formerly Twitter) @katewong

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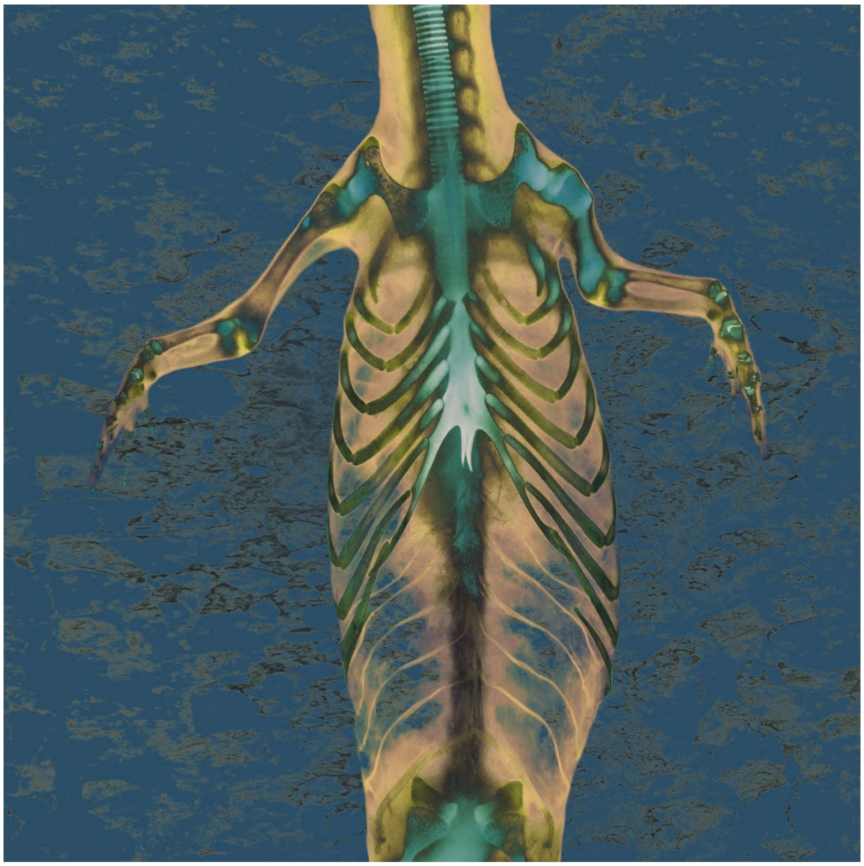
Arts

- **Poem: 'Baby Crocodile'**
  Science in meter and verse

Poem: ‘Baby Crocodile’

Science in meter and verse

By Naila Moreira & Stephen Petegorsky



Stephen Petegorsky

Edited by Dava Sobel

Tender bones, tiny soul: it could escape
in death in an instant. Itself death-dealer—
mouth of teeth, tyrannosaur
in miniature, an apparently exact copy
of its dozen nestmates—it repeats, too, time.

Yet over its life lurks the great oversoul:
the mother. She hulks. Seems to sleep. Slitty eyes,
creaking limbs, so freighted

with scales and bulk as to appear unmovable,
she tolerates our whispering observation

---

for minutes on end, gaggle of stupid tourists
closer to death than they think.
All at once she shifts. Someone has edged
too close, camera at the ready, leaning.
Her monstrous shape lunges,
wedge-head swinging, fixing

us with reptilian glare:
hard, cold, glittering, driving
as a Cadillac, and seeming as emotionless.
But that's the thing with life, we're all
the same. Repeated instances

of the same thing. This mother
is me, the surging swamp
within her the same that boils
from my gut, breast, and brain whenever
another small child strips a toy

from my son, or whacks him with a stick;
when a pickup truck cuts the corner
too close as I'm carting my child behind my bike.
Vigilant, monstrous, enormous
guardianship underlain by rage: oh this world

is too much a war, too harsh, is what
each mother, great freight of making, brooks
on the mud by black creek waters or
on the side of a shuddering mattress
when she wrests from the great nothingness a life.

Naila Moreira teaches writing at Smith College and contributes poetry, nature essays and fiction to a variety of publications. Her middle-grade novel *The Monarchs of Winghaven* is forthcoming from Walker Books.

Freelance photographer **Stephen Petegorsky** has exhibited internationally and worked with collections at Harvard's Museum of Comparative Zoology, Yale's Peabody Museum, the Smithsonian, and others.

Astrophysics

- ## JWST Spots Baby Sun Spitting Up Supersonic Flows
  A newly released image from the James Webb Space Telescope provides a detailed view of a star's infancy
- ## Alien World Denser Than Steel Confounds Our Understanding of Planet Formation
  A newly spotted world is just perplexingly dense

JWST Spots Baby Sun Spitting Up Supersonic Flows

A newly released image from the James Webb Space Telescope provides a detailed view of a star's infancy

By Lori Youmshajekian

ESA/Webb/NASA, CSA/Tom Ray (Dublin)

Shrouded in a turbulent knot of dust and gas, a fledgling star expels supersonic jets of material that stretch thousands of times the distance from Earth to the sun. This is the dramatic adolescence of HH 211, captured by the James Webb Space Telescope's Near-Infrared Camera and described in a study recently published in *Nature*.

Herbig-Haro objects, abbreviated "HH," are formed when fast-moving matter spewed from protostars collides with surrounding dust and gas, producing shockwaves "rather like a bullet going through the air," says the study's lead author Tom Ray, an astrophysicist at the Dublin Institute for Advanced Studies. These collisions excite the gas, releasing infrared light that JWST can observe.

In this image from the study, the red depicts excited hydrogen gas that rotates and vibrates at a few thousand kelvins, surrounded by green from carbon monoxide and blue from the young star's reflected light. The protostar itself sits in the rotating, dusty disk at the center of the image, where infrared radiation cannot escape because of the density of the dust and gas. Astrophysicists think the matter ejected by the wiggling jets slows the disk's spin, which allows the star to grow.

Whereas older stars like our sun blast atoms, ions and molecules into space, HH 211 ejects mostly molecular matter. Such a surprising difference can help astrophysicists understand more about how stars grow out of this critical stage of development, Ray says.

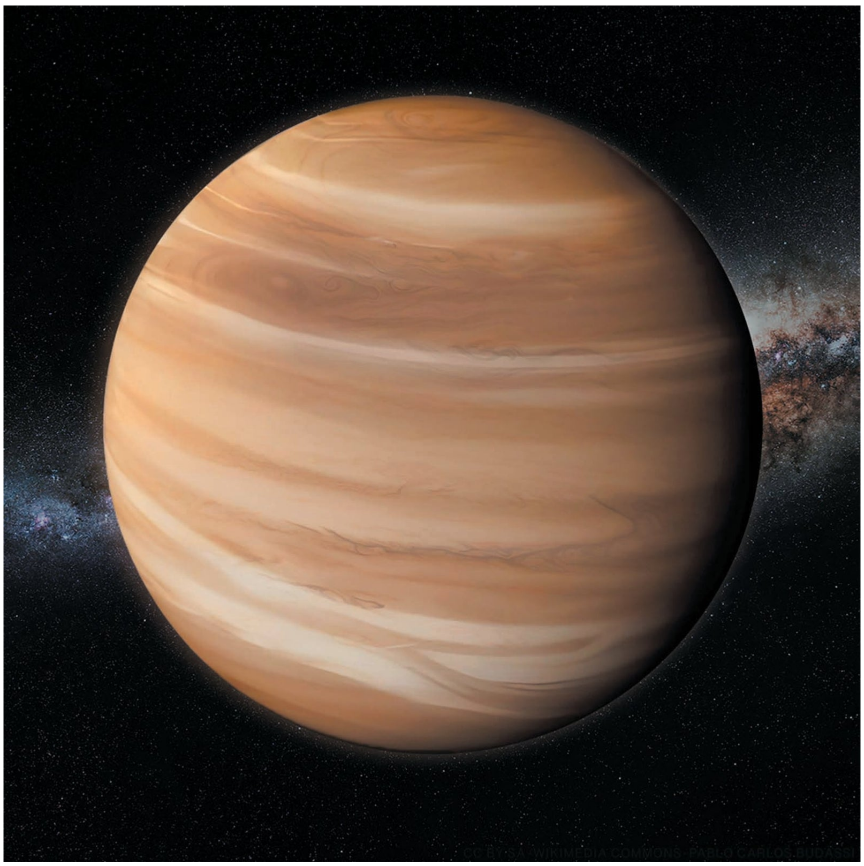
“I could stare at this for a long time,” says astrophysicist Chin-Fei Lee of Taiwan's Academia Sinica, who has previously observed HH 211 using the ground-based telescope ALMA in Chile. ALMA has observed molecular outflows, but it cannot detect any high-temperature ionized material ejected by the jets. JWST did so and produced images with much higher resolution. “This is so impressive to me," Lee says, "because we see the whole structure and the beautiful jet."

Lori Youmshajekian is a freelance science journalist who reports on advances in health, environmental issues and scientific misconduct. She holds a master's degree in Science Journalism from New York University and has written for New Scientist, Yale E360, Retraction Watch and Medscape, among other outlets.

Alien World Denser Than Steel Confounds Our Understanding of Planet Formation

A newly spotted world is just perplexingly dense

By Allison Gasparini



Pablo Carlos Budassi (*composite*); ESO/Serge Brunier (*background*)

A bizarrely dense exoplanet located more than 500 light-years from Earth is challenging scientists' understanding of how planets form. This astronomical body, recently described in *Nature*, is the size of the ice giant Neptune but nearly 10 times heavier—meaning it is denser than steel.

“It's impossible for a planet like this to have formed by classical planetary formation models,” says lead study author Luca Naponiello, a Ph.D. candidate at the University of Rome Tor

Vergata. Named TOI-1853 b, the planet is also oddly close to its sun; it rockets around the star once every 1.24 days. Neptune-size worlds are so rarely found in such tight orbits that astronomers have labeled these planet-sparse zones “hot Neptune deserts.”

The bigger mystery, though, is how TOI-1853 b got so dense. Astronomers think planets usually form “bottom-up,” with grains of rock and dust in a whirling protoplanetary disk glomming on to one another in ever larger clumps, eventually assembling a hefty core. But when that core reaches a certain critical mass, a buildup of pressure in the protoplanetary disk begins pushing additional planet-building material away, stifling further growth. TOI-1853 b seems to have somehow shot right past this limit—it has twice the amount of solid material that researchers believed could accumulate into a single object.

If conventional models can't explain TOI-1853 b, what can? Naponiello and his co-authors propose two possibilities. First, the planet may have emerged from the collision of two preexisting protoplanets. Such collisions are expected in a planetary system's early epochs, but they are more likely to leave behind multiple planets than to result in a single, larger world, Naponiello says.

The second possibility is that TOI-1853 b began as a gas giant about the mass of Jupiter before losing most of its atmosphere to intense stellar radiation, ending up as a stripped-down solid core.

Indeed, if this planet once had a sizable atmosphere, very little remains. That makes it unique even among Neptune-size planets, says astronomer Chelsea Huang of Australia's University of Southern Queensland. Huang finds the gas-giant theory particularly intriguing, as such planets' thick atmospheres typically obscure what's happening deeper inside. If TOI-1853 b once was a gas giant, then “this is the only way we can actually observe [a gas giant's] interior,” Huang says.

Future analysis of the planet's remaining atmosphere could reveal whether either of these hypotheses is correct. If TOI-1853 b was formed by collisions, researchers would expect its atmosphere to include water and other volatile compounds. If instead it was once a gas giant, they would expect to see a relatively thin, hydrogen-dominated atmosphere.

Allison Gasparini isa science writer who has written for *Forbes*, *Science News*, NASA, Brookhaven National Laboratory, the American Institute of Physics, Stanford University, and more. Follow her on Twitter @astrogasparini

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  Lunar influences, parallel universes, taking over a dead relative’s online identity, and more books out now

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How to Escape a Time Loop You Don’t Really Want to Leave

A tender novel about savoring quantum memory

By Meg Elison

Chanelle Nibbelink

Edited by Amy Brady

FICTION

A Quantum Love Story
by Mike Chen
MIRA, 2024 ($30)

On supporting science journalism

Time and grief are two inexorable companions in life, even when we are falling in love. It is truths like this one that set the scene for *A Quantum Love Story*. Tragedy has already struck when the novel begins, as neuroscientist Mariana Pineda has just lost her best friend, Shay. Carrying Shay's framed portrait, Mariana is headed to marvel at the new Hawke Accelerator with the team from ReLive, an experimental program that allows people to reenter their memories and live those moments once again. Mariana has given up her old life to start working at ReLive just before disaster hits.

One morning she runs into Carter Cho, a mysterious man bearing doughnuts and a surprising amount of knowledge about who she is and what she's after. Carter tries to explain something to her about how they've been there before and how he needs her to remember. Carter, who has an eidetic memory, can do nothing but remember. He knows what's about to happen: there's going to be an explosion at Hawke, and time is going to bend around them in a time loop that restarts every four days.

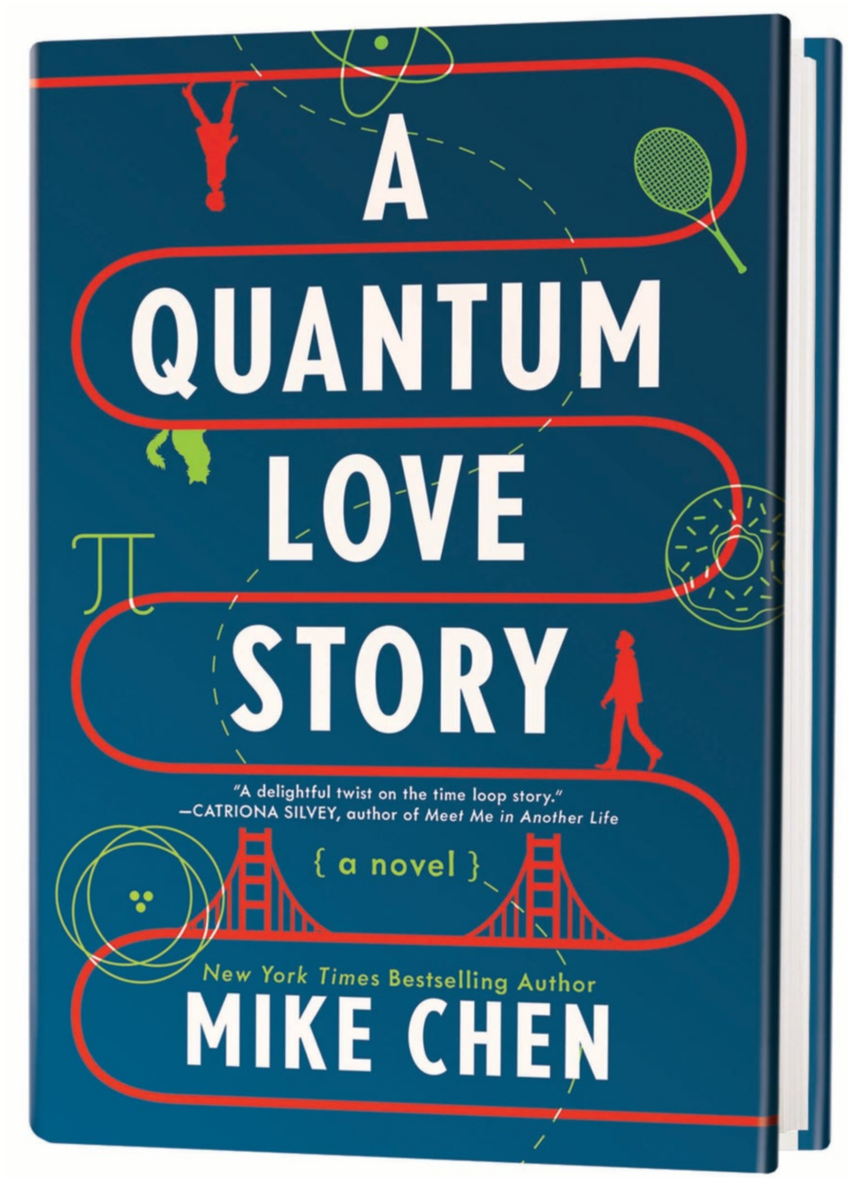
This emotional new novel from Mike Chen combines what is best about science fiction, mystery and romance. The concept at the heart of *A Quantum Love Story* is that time, memory and consciousness are all similar substances, both stubborn and fluid. The mystery to be solved is at once simple (how did we get here?) and deeply complicated (how far back do we have to go to change the conditions in which we live now?). The romance is built on the smallest daily intimacies: cooking and going out to eat, meeting one another's pets, playing tennis, and trying to hold these pleasures even as time works against the lovers to take everything from them over and over again.

Chen's body of work—including his previous books *Here and Now and Then* and *Star Wars: Brotherhood*—is growing in distinction largely thanks to his ability to spin human frailty into a golden webwork between the concepts of space and time. His prose choices create a friendly, highly accessible understanding of character and setting. The result is a world rendered in Technicolor, every corner lit, every scene set so that the reader can walk right in. Chen's charming characterizations are at their best in cooperative relation to one another: Carter and Mariana give off that slow-burn ozone long before they ignite, and even the story's AI presence (a helpful yet coy assistant patterned after the late David Bowie) is endearingly tender.

People who enjoyed reading *The 7 1/2 Deaths of Evelyn Hardcastle*, by Stuart Turton, or who watched the Netflix series *Russian Doll* will anticipate the bittersweetness of this time-loop romance. It both resembles real life and distorts it, giving us the chance to contemplate both the mundane sameness and the numinous qualities of our daily lives. Fans of Audrey Niffenegger's *The Time Traveler's Wife* will foresee the frustration and peril ahead; although Mariana and Carter can accept and enjoy the loop they're in, nothing lasts forever, even when time stands still.

Carter, despite his visual memory, is the first to break. Keeper of the watch, he's been the one to track all the things they've done within the confines of their repetition to avert the disaster that landed them here. When he starts to forget their previous loops, Mariana realizes they can't keep looping indefinitely. The stakes go beyond the two of them: The entire time line is at risk as they uncover the dangers of ReLive's design flaws and memory medicine. One of them is going to have to make a considerable sacrifice. But if that means losing each other, Mariana isn't sure she can do it. Add to that the possibility that she might be able to save Shay, and the dilemma of the novel's final act is set.

Readers who crave hard-shell explanations of time travel or who need to know exactly what mechanism causes the continuum to loop and create an eddy will have to look elsewhere. Chen is not that kind of writer. Although the science of memory and the brain comes across as well researched and intriguing, the realm of quantum mechanics remains a cosmological question mark. Readers who enjoy the difficult questions about how we move through time with a great deal of love (and very little control), however, will appreciate how Chen builds a skiff made of paper to sail through the storm. The twin companions of time and grief are not the adversaries they seem, and Carter and Mariana have more fodder for reconciliation than for fighting. We arrive at the end of the book with our hearts bruised but intact.



Meg Elison is a novelist and essayist based in Brooklyn, N.Y. Her debut novel, *The Book of the Unnamed Midwife*, won the 2014 Philip K. Dick Award. Her latest book is *Number One Fan* (MIRA, 2022).

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How the Moon Shaped Human History, from Religion to Climate

Lunar influences, parallel universes, taking over a dead relative's online identity, and more books out now

By Amy Brady

Onkamon Buasorn/Getty Images

NONFICTION

Our Moon: How Earth's Celestial Companion Transformed the Planet, Guided Evolution, and Made Us Who We Are

by Rebecca Boyle
Random House, 2024 ($28.99)

A few days a month the moon rises as a fat pearl above us. "If you're lucky," Rebecca Boyle (a contributor to *Scientific American*) writes in her new book, "you will see a few hundred of these in your life." It's a quick sentence whose sentiment—like the silvery orb it conjures—might pass you by: our lives are finite; our lives are marked in moons. This is a poetic revelation in itself, but

Boyle's project is far more ambitious. Not only does she show how the moon scaffolds our years, but she reveals its sway over just about every facet of our history, including scientific discovery, religion, climate, physiology, psychology and evolution, with gravitational tides nudging our distant fish relations to walk. Its cycles of departure and return helped early humans grasp concepts such as “becoming, birth, vanishing, death, resurrection, renewal, and eternity.” Shared lunar knowledge was our ancestors' Google calendar, helping them to coordinate the hunts, harvests and ceremonies that allowed societies to coagulate. Our moon, Boyle writes, has done nothing less than enable “the beginning of history.”

In the hands of a less deft writer, sentences like that one might raise red flags of hyperbole. But Boyle's command of her subject is so clear, her journalistic instincts and interdisciplinary research so impressive, that readers will have no qualms about learning to see their world through a moon-colored lens. Boyle structures the book in three sections: how the moon was made, how the moon made us and how we made the moon in our image. “There is no story about the Moon that does not tell us something about Earth,” Boyle writes. From Mesopotamian priests to the Apollo program's “white Protestant men who ... drank whiskey from highball glasses,” she surveys those who have defined our lunar view, guiding us to the precipice of its uncertain future. As governments and billionaires scheme for a moon-based economy, Boyle considers who gets to determine the future of this “limited, special, spectral, spiritual thing.”

The moon cannot be reduced to a resource or a divine symbol. It is its own place—all of ours, Boyle writes, which means it's also none of ours. Even now it's spiraling away from Earth at roughly the rate of fingernail growth. Six hundred million years from now it will be too far away to eclipse the sun. —*Erica Berry*

IN BRIEF

Exordia
by Seth Dickinson
Tor, 2024 ($29.99)

In Seth Dickinson's 2015 debut novel, *The Traitor Baru Cormorant,* a fiercely willful woman from a colonized island plots her revenge against a brutal empire. This fascination with weighing the value of specific lives against a greater good also powers his new book, a mind-shredding first-contact epic. A spaceship or weapon or *something* has appeared in Kurdistan, where its mysteries get puzzled over by a sprawling cast. There are nukes, alien brain locks, intergalactic warfare and a scope that keeps expanding long after the stakes seem clear. This thrilling novel grips hardest when Dickinson's characters must reason through the science of seemingly impossible phenomena. —*Alan Scherstuhl*

Dead in Long Beach, California: A Novel
by Venita Blackburn
MCD, 2024 ($27)

After discovering her brother Jay's suicide, Coral, a Black, gay graphic novelist with biting wit, assumes his identity. She texts Jay's friends and daughter from his phone and creates social media accounts in his name, all while burying herself in the banality of daily life. Coral's escapades are interwoven with snippets from her own novel, *Wildfire*, a tale of a dystopian, alien world that gradually infiltrates Coral's actual reality. Those excerpts occasionally meander, but author Venita Blackburn's prose is stunning, sensitive and that-made-me-snort funny. Richly layered and ambitiously structured, this unconventional novel about death and denial is bizarre in the best way. —*Lucy Tu*

The Allure of the Multiverse: Extra Dimensions, Other Worlds, and Parallel Universes
by Paul Halpern
Basic Books, 2024 ($30)

Physicist Paul Halpern has noticed the public's fixation with the multiverse—take *Everything Everywhere All at Once* winning seven Oscars in 2023, for instance. Such popular science fiction serves as a launchpad for Halpern's crash course on the strange physics behind multiple-universe theories. His lively synthesis of millennia of scientific debate humanizes prominent theorists such as Theodor Kaluza and Brandon Carter, and his analogies—such as a bickering couple to illustrate renormalization—simplify heady concepts. It's still a dense read, but it's worth the exertion: more of an *Interstellar* blockbuster than a *Rick and Morty* episode. —*Maddie Bender*

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

Climate Change

- ## As the Climate Crisis Deepens, High-Polluting Nations Must Start Paying Reparations
  The wealthy countries that are most responsible for greenhouse gas pollution must compensate the poorer nations that bear the greatest burden
- ## The World Solved Acid Rain. We Can Also Solve Climate Change
  Lessons from how we tackled acid rain can be applied to our world today

As the Climate Crisis Deepens, High-Polluting Nations Must Start Paying Reparations

The wealthy countries that are most responsible for greenhouse gas pollution must compensate the poorer nations that bear the greatest burden

By The Editors

James Yang

The U.S. got a powerful reminder last summer that pollution doesn't care about borders. Smoke from wildfires blazing across Canada billowed hundreds of miles south, painting skies from New York City to Chicago and beyond a hazy orange and damaging air quality to the point that health officials were warning people not to go outside.

Greenhouse gas pollution is similar—not governed by borders, warming the planet indiscriminately and damaging the climate on an extremely broad scale. In this era of climate crisis, in which decades' worth of carbon pollution from rich nations is magnifying natural disasters, poorer countries are paying some of the steepest costs.

It's time to start compensating these countries. The United Nations recently decided to address this issue through its yearly climate gathering, the Conference of the Parties, or COP. At COP27 in November 2022, world leaders agreed to create a fund for loss and damages for climate disasters, and attendees at 2023's COP28 planned to further the conversation. But climate diplomacy can be slow, and it will be tough to make these reparations a reality.

Nevertheless, the U.S. and its carbon-spewing counterparts must pursue climate reparations to right the wrongs of carbon pollution and help lower-income nations weather the climate emergency.

Reparations, broadly understood, are payments offered to make up for loss or damage, and they can be a touchy subject for a range of legal and psychological reasons. They are just one of several funding mechanisms through which we can try to ease the unequal burden of climate change, including some that focus specifically on climate mitigation or adaptation. But whatever the term, the science is clear on the necessity of these payments.

Scientists estimate that worldwide, humans produced nearly 2.5 quadrillion kilograms of carbon dioxide between 1851 and 2021.

Analysis after analysis has shown that over time the U.S. has produced by far the most heat-trapping gases—17 percent of the global total. This astronomical amount equals the combined emissions produced by more than 20 developed nations, including Germany, Japan and Australia. In comparison, climate emissions from 47 of the least developed countries add up to just 6 percent of the total. China ranks second among individual countries, at 12 percent of total emissions, but it began industrializing much later than the U.S. Because of China's large population, the country's per capita emissions are slightly more than half of those of Australia, Canada or the U.S.

Although industrial countries occasionally pledge to solve these problems, they still bicker about how much climate disruption they are willing to permit, and they haven't put their money where their promises are. Wealthy nations have pledged to fund projects to mitigate climate change such as expanding clean energy, as well as adaptation projects such as building seawalls. They've promised $100 billion a year for these kinds of projects, but the funding hasn't materialized. And because industrial countries have opposed decarbonization for so long, mitigation and adaptation are not enough.

People are already dying from the consequences of carbon pollution that developed nations generated while amassing their wealth. For example, last September a hurricanelike storm from the Mediterranean drenched Libya with one year's worth of water in a single day. Two dams collapsed, and at least 4,000 people died, although the true toll might be closer to 10,000. Scientists have determined that such a disaster—a one-in-600-year flood—is 50 times more likely today than it was when the planet was 1.2 degrees Celsius cooler.

“By delaying the discussion, we have accepted that people can die and that enormous harm can happen at the global level,” says

Joyeeta Gupta, a sustainability scientist at the University of Amsterdam.

Scientists are also clear on the role this pollution plays in exacerbating disasters, both in general and for individual cases. Hundreds of studies have sought to quantify the contribution of climate change to specific disasters. The majority of such studies on heat waves show that these events are becoming more likely or more severe as climate upheaval continues. Around half of the studies on heavy rainfall and flooding or on drought reach that same conclusion.

As the climate crisis worsens these kinds of events, their toll becomes ever steeper. In 2022 Earth experienced about 40 billion-dollar disasters, including Hurricane Ian in the southeastern U.S., devastating floods in Pakistan and drought in eastern Africa. The U.S. bears more of the responsibility for these crises and boasts more resources for responding to them, whereas countries across the developing world lack the wealth, insurance infrastructure and government programs needed to recover from disaster. Meanwhile the slower-moving calamity of sea-level rise is eating away the tiny homelands of small island nations, which might soon begin facing the steep costs of involuntary relocation.

We call on those who have become rich at the expense of a less livable world to prioritize the needs of developing countries and others bearing the brunt of the climate crisis. At home and abroad, there's no time to wait. The science is clear: the industrial world is responsible. The least we can do is pay for the damage we've done.

The World Solved Acid Rain. We Can Also Solve Climate Change

Lessons from how we tackled acid rain can be applied to our world today

By Hannah Ritchie


Thomas Fuchs

The world feels like it's being set alight; wildfires in Canada and Europe, floods in China, and a never-ending stream of recording-breaking heat waves have garnered numerous headlines.

The feeling that time is quickly running out is very real. And it's easy to believe that the world cannot tackle big environmental problems. This sense of helplessness is something that I have personally battled for more than a decade. But that feeling is a barrier to action: Nothing has changed when we've called for action before, so why should we expect any different this time?

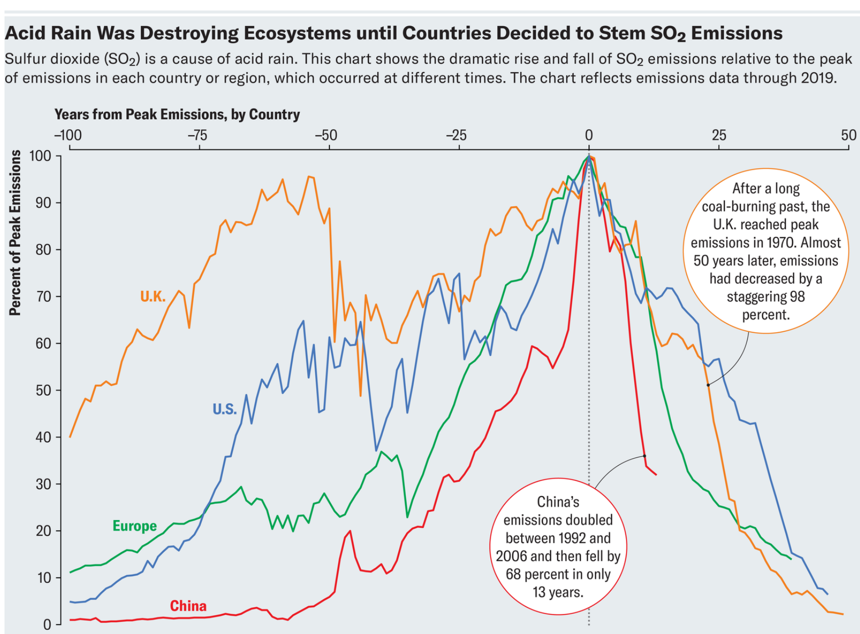
But our past efforts tell us there is hope. The world has solved large environmental problems that seemed unsurmountable at the time. In my role at Our World in Data, I've spent years looking at how these problems have evolved, and I think that it's worth studying these issues, not only for hope, but to understand what went right and what can help us face today's crises. An eye-opening example is acid rain; studying how the world tackled this geopolitically divisive problem can give us some insights into how we can tackle climate change today.

It has mostly slipped from the public conversation, but acid rain was *the* leading environmental problem of the 1990s. At one point, it wasone of the biggest bilateral diplomatic issues between the United States and Canada.

Acid rain—precipitation with high levels of sulfuric or nitric acids—is mostly caused by sulfur dioxide, a gas that is produced when we burn coal. It had severe effects on ecosystems. It dissolved old sculptures, stripped forests of their leaves, leached soils of their nutrients, and polluted rivers and lakes. Emissions from the U.K. would blow over to Sweden and Norway; emissions from the U.S. would blow over to Canada. Just like climate change, it crossed borders, and no country could solve it on its own.

This is a classic game theory problem; outcomes don't only depend on the actions of one country but on the actions of the others too. Countries will only act if they know that others are willing to do the same. This time, they did act collectively. Government officials signed international agreements, placed emissions limits on power plants and started to reduce coal burning. Interventions were incredibly effective. In Europe, sulfur dioxide emissions fell by 84 percent and in the U.S. by 90 percent. Some countries have reduced them by more than 98 percent.

We did something similar with the ozone layer. The ozone hole was a big coordination problem. No single country was responsible for the world's emissions of ozone-depleting substances. So there was little upside and some downside to countries taking the lead on their own. They would spend money and implement unpopular environmental policies without making much of a dent in the global problem. The only way to cut emissions substantially was for many countries to join in. It relied on international collaboration. Yet the world solved it. After countries signed the Montreal Protocol, emissions of ozone-depleting substances fell by more than 99 percent.



Credit: John Knight; Source: Data Explorer: Air Pollution, Our World in Data

What we learned from tackling acid rain and the ozone hole can be applied to tackling climate change overall.

First, the cost of technology really matters. The cost-benefit ratio of desulfurization technologies was key to solving acid rain. The cost of installing scrubbers was significant but not budget-breaking. If they had come at a huge cost, countries wouldn't have made the switch.

Similarly, cheap low-carbon technologies are essential for climate change. Low-carbon technologies used to be expensive, but in the last decade the price of solar energy has fallen by more than 90 percent . The price of wind energy by more than 70 percent. Battery costs have tumbled by 98 percent since 1990, bringing the cost of electric cars down with them. Globally, one in every seven new cars sold is electric. In Europe, one in every five, and in China one in every three.

At the same time, countries are waking up to the potential costs of not moving to clean energy, whether in the form of climate damages—at home or overseas—or being tied to volatile fossil fuel markets.

Second, climate agreements and targets take time to evolve. Negotiations are long. The ozone hole and acid rain were not fixed with the first international agreements on the table. The initial targets were too modest to make a large enough difference. But over time, countries increased their ambitions, amended their agreements and reached for those higher goals.

This is a basic principle of the Paris climate agreement. Countries agreed to step up their commitments to keep global temperature rise below 1.5 degrees Celsius or 2 degrees C. While this has been happening, it definitely hasn't happened fast enough. The world is on track for an increase of around 2.6 degrees C by 2100. That's extremely bad. But it's still a degree lower than where we were heading in 2016. Governments have increased action and increased their target numbers too. And just like with acid rain or the ozone hole, they need to keep aiming higher. If every country fulfilled its pledges, the world would keep temperature rise to 2 degrees C. If they met their net-zero commitments on time, we could sneak below it.

Finally, the stance of elected officials matters more than their party affiliation. Environmental issues do not have to be so politically divisive. Acid rain was a bipartisan divide in the U.S. under Ronald Reagan's presidency. But it wasn't a Democrat who finally took action; it was his Republican successor, George H.W. Bush. Before taking office, Bush pledged to be the "environmental president," a bold stance for many right-wing leaders today, but one that we need to see repeated if we are going to make and reach these loftier goals. In the U.K., there is strong public support for net-zero emissions even among the political right. Margaret Thatcher—arguably one of the U.K.'s most right-wing leaders ever—was one of the earliest to take climate change seriously.

Former German chancellor Angela Merkel is a modern example of a pro-climate conservative leader. A scientist by training, Merkel always acknowledged the threats of climate change, gaining the title of "climate chancellor." In the late 1990s she led the first U.N. climate conferences and the Kyoto Protocol. In 2007, she convinced G8 leaders to set binding emission reduction targets. It's wrong to frame environmental problems as right-left wing issues. If we're going to tackle climate change, we need to overcome this divide.

Climate change is not the perfect parallel for the environmental problems we've solved before. It will be harder; we should be honest about that. It means rebuilding the energy, transport and food systems that underpin the modern world. It will involve every country, and almost every sector. But change is happening, even if it doesn't hit the headlines. To accelerate action, we need to have the expectation that things can move faster. That’s where past lessons come in; we should use them to understand that these expectations are not unrealistic. Change can happen quickly, but not on its own; we need to be the ones to drive it.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

A version of this article with the title “What We Learned from Acid Rain" was adapted for inclusion in the January 2024 issue of Scientific American.

Hannah Ritchie is deputy editor of the online web publication Our World in Data. She is a senior researcher at the University of Oxford. Her book *Not the End of the World* will be published this month by Little, Brown Spark.

Cosmology

Vitamin D Hope and Hype, Cosmic Voids and Preventing Depression

Alaska’s rusting rivers, einstein tiles and the new science of asexuality

By Laura Helmuth

Scientific American, January 2024

Have you ever gotten a blood test result saying your vitamin D levels are low? Or heard that the vitamin is a miracle cure? It turns out fears about deficiencies, and hopes of the vitamin's healing power, have been wildly overblown. Author Christie Aschwanden explains why the evidence has pointed one way and then the other, and why blood tests can be misleading, in a story full of insights about the advancement of science. You need some vitamin D, though probably not supplements. We make vitamin D when sunlight hits our skin, like a human form of photosynthesis. The best way to get it, if you are able, is to spend more time outdoors—which tends to make everything better.

Prepare to look at the night sky in a different way after reading Michael D. Lemonick's article. The universe is full of ... voids. They are empty spaces where almost nothing currently knowable exists. Mike is a former editor at *Scientific American* and a longtime physics writer (and the nicest guy), and he's been following the mystery of the cosmic voids for decades. When they were discovered, they blew astronomers' minds, but now we have enough data and computing power to study these empty spaces, which could improve our understanding of gravity, dark matter and dark energy.

Depression can be a debilitating, chronic, episodic condition, and preventing it could save money, health and lives. Now there's strong evidence that prevention programs can help. Screening teenagers and helping at-risk kids learn emotional and cognitive skills can reduce the risk of early signs turning into mental illness. Science writer Elizabeth Svoboda discusses how to build these skills and why a focus on fixing rather than preventing problems makes it difficult for school systems to implement such programs. We hope our article will help broaden support for these kinds of initiatives. Prevention rarely gets as much appreciation as it deserves.

The photographs of Alaska's rusting rivers are real—the rivers really do look brilliant orange, and that is literally rust. Climate journalist Alec Luhn accompanied scientists studying these bizarre rivers to figure out what is causing the discoloration, and photographer Taylor Roades used drones to capture the scenes. Alaska is warming even faster than the Lower 48, and thawing permafrost there is changing ecosystems dramatically. Acid from newly exposed bedrock could be leaching out iron that later forms rust, or it might be bacteria or some other force.

Until recently, a general lack of feeling sexually attracted to others was often considered a psychological problem in itself or a symptom of some other disorder. Now asexual people and researchers who study asexuality have shown that it is just another way to be human. Allison Parshall, a writer and editor who works with us frequently (she edited this issue's Advances department), has a thoughtful story about the new cultural and scientific awareness of asexuality and how it is opening up new social norms.

You may have read about the discovery of a long-sought mathematical shape called an einstein tile that can cover an infinite surface without repeating a pattern. I thought I'd heard all about it ... but then I read computer scientist Craig S. Kaplan's account of its discovery. It is a delightful narrative, full of dramatic tension and charismatic characters who are having an absolute blast pursuing a new understanding of tiling patterns. The illustrations by Miriam Martincic are inspired by M. C. Escher, the artist whose dazzling repeated patterns were popularized in the U.S. by *Scientific American.* Enjoy the challenge of mentally fitting these pieces together in your own mind.

Contributors to *Scientific American*'s January 2024 Issue

Writers, artists, photographers and researchers share the stories behind the stories

Credit: Taylor Roades

Taylor Roades Rusting Rivers

Last summer photojournalist Taylor Roades traveled to Arctic Alaska to capture the region's contaminated waterways in startling color. Before the trip, she had seen only an aerial smartphone photograph of these rivers, featured in Alec Luhn's article about the mysterious climate change–driven processes polluting them with rust. Roades, who has been camping in the Canadian backcountry since she was a child, ran through most of her drone's battery life early in the trip—surely the orange-tinted rivers they were seeing were as bad as it would get? Then, around day four, she and the team of scientists reached swaths of blackened land where vibrant orange sludge seeped from the ground like lava. “That was shocking,” even for the scientists, she says.

Roades grew up in Toronto but moved west to British Columbia in 2013 in a “very conscious effort” to immerse herself—and her photography—in forests and oceans. Her work has documented Canada's “forgotten rainforests” where old-growth trees are threatened by logging and a coastal B.C. First Nation that is reclaiming and protecting its ancestral land. In a world rocked by climate change and environmental degradation, this work feels like a moral imperative. “What am I going to say to my future kids?

That I did nothing or that I put my effort and skills into stopping it?”

Michael D. Lemonick **Cosmic Nothing**

Mike Lemonick's father was his own personal Carl Sagan, a physicist who fostered his son's love of the cosmos with stories of Halley's Comet. The comet was overhead when Mark Twain was born and then again as he lay on his deathbed, or so the story goes. The comet was coming again in 1986—”the distant future, or so it seemed to me in the 1950s,” Lemonick says. That appearance turned out to be a dud, “but by then I was hooked.” In 1986 he was an editor at the magazine *Science Digest* when a non-comet-related revelation rocked the field of cosmology: matter isn't evenly spread through the universe, as previously thought, but clumps together into clusters.

In the ensuing decades, those clusters received almost all the attention. But what about the voids they left behind? “They were ignored for decades,” says Lemonick, a lecturer at Princeton University and a former *Scientific American* editor. For this issue, he wrote about the physicists who are shining a spotlight into these voids to solve some of cosmology's biggest mysteries. “It's a very old story,” he says—yet also, somehow, brand-new.

Martin Krzywinski **Cosmic Nothing**

A lifelong stargazer, Martin Krzywinski was fascinated by anything to do with astronomy, first as a child in Warsaw, Poland, and then in Canada. So when he stumbled on a video five years ago about something called the Boötes void, he was intrigued. He knew Boötes as the kite-shaped constellation that hosts the star Arcturus. But that this familiar constellation contained a massive swath of cosmic nothingness was entirely new to him. “It was like love at first thought,” he reflects. “I can't let this go.” Krzywinski, who alternates between calling himself an artistic scientist and a scientific artist, immediately began crafting a map of empty spaces such as the Boötes void across the universe, which he has adapted into a graphic for this issue.

The big illustration challenge was giving these empty spaces character; most don't even have names. To Krzywinski, that's all the more intriguing. “What really interests me are these giant places far away that are difficult to imagine,” he says, because that imagination fosters an emotional connection. “I'm more likely to emotionally relate to something that is unseen and unknowable.”

Christine Aschwanden **The Rise and Fall of Vitamin D**

Thirteen years ago Christie Aschwanden wrote a cover story for *Reader's Digest* debunking the health benefits of multivitamins. “I think it set a record for the most angry letters to the editor,” she recalls—not because anything was incorrect but because many people are very attached to their vitamins. “There was a time when we thought that if we could just get everyone's vitamin D levels up, that could really improve overall health,” she says.

As Aschwanden shows in her article, it is now clear that vitamin D may be associated with good health but is probably not its cause. Most of us get plenty of the substance without supplements. While reporting the story, she was surprised to learn how many of her friends and loved ones had recently been told they were deficient in vitamin D by their doctors. The idea “that vitamin pills are somehow magic elixirs—it's very tempting,” she says. “We're all after that one weird trick.”

Laura Helmuth is editor in chief of *Scientific American*. She previously worked as an editor for the *Washington Post*, *National Geographic*, *Slate*, *Smithsonian* and *Science*. She is a former president of the National Association of Science Writers. She is currently a member of the National Academies of Sciences, Engineering, and Medicine's standing committee on advancing science communication and an advisory board member for SciLine and The Transmitter. She has a Ph.D. in cognitive neuroscience from the University of California, Berkeley. She recently won a Friend of Darwin Award from the National Center for Science Education. Follow her on Bluesky @laurahelmuth.bsky.social

Culture

Science News Briefs from around the World: January 2024

Deciphering a scorched scroll from ancient Herculaneum, unlikely flavors in climate-change-affected wine, an undiscovered ore found in China, and more in this month’s Quick Hits

By Lori Youmshajekian

ANTARCTICA

Ice-penetrating radar has revealed a landscape of valleys and ridges hidden under nearly two miles of ice in East Antarctica. Before the continent froze over about 34 million years ago, the region might have hosted tropical-like forests and wildlife.

CHINA

Geologists have discovered a new ore called niobobaotite near the city of Baotou in Inner Mongolia. The ore contains the rare transition metal niobium, which is used in steel production and becomes a superconductor when cooled to low temperatures.*

ETHIOPIA

A child's jawbone uncovered decades ago in the Ethiopian Highlands has been identified as a two-million-year-old *Homo erectus* fossil. Discovered more than 6,500 feet above sea level, the find suggests that larger-bodied *H. erectus* might have been better adapted to higher altitudes than other early hominins were.

FRANCE

Critics gave higher ratings to Bordeaux wine made in years with greater temperature extremes and a higher mean temperature. But the area's climate might become too hot and too dry for grapes to grow at all, and vineyards are increasingly impacted by floods, wildfires, and other severe events.

INDONESIA

Indonesians who survived the region's devastating 2004 tsunami have lower levels of the stress hormone cortisol than those who didn't directly experience the disaster. This “hormonal burnout” demonstrates how traumatic events can affect people for decades afterward.

ITALY

For the first time, an artificial-intelligence program has deciphered a word from a badly scorched scroll from Herculaneum, one of the cities buried by the eruption of Mount Vesuvius about 2,000 years ago. By distinguishing ink from the background of blackened papyrus, the technique uncovered the word “*porphyras*”—ancient Greek for “purple.”

**Editor’s Note (3/7/24): This sentence was edited after posting to correct the description of niobium.*

Lori Youmshajekian is a freelance science journalist who reports on advances in health, environmental issues and scientific misconduct. She holds a master's degree in Science Journalism from New York University and has written for New Scientist, Yale E360, Retraction Watch and Medscape, among other outlets.

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Readers Respond to the September 2023 Issue

Letters to the editors for the September 2023 issue of Scientific American

Scientific American, September 2023

INTELLIGENCE PROBE

In “An AI Mystery,” George Musser makes multiple references to “probes” that can examine the methods an artificial-intelligence model uses to produce its output. Does this not effectively solve the “black box” problem that is often cited by AI experts—that is, the problem of our inability to know how an AI reaches a certain conclusion? How is the hypothetical black box different from the inner workings of AI revealed by these probes?

ELISE CORBIN *TORONTO*

On supporting science journalism

MUSSER REPLIES: *Probes don't solve the black box problem on their own—they're just one research tool. They can reveal how groups of artificial neurons in a network encode higher-level information, such as parts of speech or positions on a chessboard. Researchers first decide what information they want to look for and then design a probe to detect it and translate it into a human-readable form. The probe can resolve whether a network is merely parroting its training data or recognizing the patterns within it. But probes reveal only the presence of information, not how, or even whether, the network uses it to reach a conclusion. Researchers must still trace how information flows through the system.*

BLACK HOLE DONE

In “Disappearing Act” [Advances], Adam Mann discusses the evaporation of black holes, among other things. I have wondered what happens when an evaporating black hole's mass has decreased to the point where its gravity is no longer strong enough to prevent the escape of electromagnetic radiation. Does the remainder of the black hole become visible? What does it look like? What is the remaining matter?

GLENN P. DAVIES *HAMILTON, ONTARIO*

THE EDITORS REPLY: *Current theories suggest that at a certain, extremely small minimum mass, an evaporating black hole will emit a burst of gamma rays as its “last gasp” before vanishing from existence. Evaporation occurs so slowly that all known black holes would require far longer than the age of the universe to reach* *this point. Consequently, astronomers have used the nondetection of telltale gamma-ray outbursts to estimate limits of the abundance of hypothetical low-mass primordial black holes that may have formed shortly after the big bang.*

VACCINE IMPROVEMENT

As a physician and vaccinologist, I am thrilled that scientists have mastered the ability to differentiate protective and disease-enhancing forms of respiratory syncytial virus (RSV) F protein, as described in "The Long Shot," by Tara Haelle. This advance has made possible the construction of safe and protective RSV vaccines that avoid vaccine-associated enhanced disease (VAED), some of which have been recently licensed. The phenomenon of VAED comprises two rather different immunopathologies: antibody-dependent enhancement (ADE), which I discovered in the late 1970s, and vaccine-associated hypersensitivity (VAH). Intrinsic ADE contributes to dengue infections because dengue viruses form immune complexes with the antibody immunoglobulin G. These complexes establish productive cellular infections in macrophages that result in the release of high concentrations of toxic NS1, a viral protein that damages cells' endothelium and produces dengue shock syndrome. A number of vaccine constructs have yielded VAH breakthrough tissue infections, sometimes with lethal immune responses, such as formalin-inactivated measles and earlier RSV vaccines given to children, as well as killed SARS and MERS vaccines given to monkeys.

SCOTT B. HALSTEAD *WESTWOOD, MASS.*

DEMENTIA AND CREATIVITY

Thanks for Robert Martone's Mind Matters article, "Dementia Can Unleash Creativity." My mother-in-law, as her Alzheimer's disease advanced, could spout reams of reasonable poetry off the top of her head. She had no previous inclination to write at all. I could never understand poetic creativity, let alone in someone who needed help to do basic living tasks. It's nice to know that she wasn't the only one. I wonder if some of the hallucinogenic drugs might work in a similar fashion.

EDWIN HAWKINS *VIA E-MAIL*

DUSTY BEAUTY

In “Celestial Wonders,” Peter Tuthill provides us with an almost unbelievable side-by-side comparison of images of dust surrounding a binary-star system. One portrayal is a complex computer simulation, and the other is an image of vibrant bands of bright colors received from the James Webb Space Telescope. They seem to match perfectly and are equal in beauty. My appreciation for theoretical physicists and their ability to echo the real world keeps expanding.

JOSEPH S. NARDELLO *MEDFORD, N.J.*

AI DON'T THINK SO

In “Safeguarding AI Is Up to Everyone” [Science Agenda], the editors state, “Fundamentally, AI is a computing process that looks for patterns or similarities in enormous amounts of data fed to it.” I find it difficult to accept this definition of AI as valid because I believe that intelligence is the opposite of rote data crunching: it is about creating novel ideas out of limited, incomplete and contradictory data or even no preexisting data at all. I think we should deflate the current AI hype by emphasizing this essence of intelligence.

Regulation should cover all systems or products that produce a “humanlike” output. Requiring that such systems or products include indelible source marks in their output should go a long way toward preventing abuse and fraud. Maybe the method for hiding content in text and images described in “Out of Sight,” by Dina Genkina [Advances], could be used to create such digital watermarks. Also, the Content Authenticity Initiative (CAI) is providing an open standard for embedding content credentials into various files. Camera manufacturers are already bringing products to market that include the ability to insert content credentials into original photographs.

ROBERT BRUN *HARD, AUSTRIA*

BUILT TO LAST

Naomi Oreskes's excellent article “Social Security and Science” [Observatory, May 2023] packs more information, history and wise commentary into one printed page than I would have thought possible. Being almost 80 years old, I especially enjoyed her praise of productive old things that simply need a small adjustment now and then to remain useful.

JAMES LUCE *ALT EMPORDÀ, CATALONIA*

ERRATA

“Lawn Gone,” by Jesse Greenspan [Advances], incorrectly said that no mammals were observed at the study site. As shown in the related graphic, bats were observed. During one night of searching, no small wingless animals were found.

In “A Stratospheric Gamble,” by Douglas Fox [October 2023], the graphic depicting the Intertropical Convergence Zone and trade winds incorrectly represented midlatitude atmospheric circulation cells called Ferrel cells. The corrected illustration can be seen at https://www.scientificamerican.com/article/its-time-to-engineer-the-sky

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Ecology

- **How a Parasitic Worm Forces Praying Mantises to Drown Themselves**
  Thieving worms may manipulate their prey with stolen genes

How a Parasitic Worm Forces Praying Mantises to Drown Themselves

Thieving worms may manipulate their prey with stolen genes

By Darren Incorvaia

Horsehair worm and its mantid host.
Takuya Sato

For a praying mantis, eating the wrong insect can be a one-way ticket to a watery grave. Some of its typical bug prey contain horsehair worms, *Chordodes fukuii*, which grow in a mantid's gut—and somehow manipulate the mantid into diving into the nearest body of water. The spaghettilike worms then wriggle free of their drowned host and reproduce. Aquatic insects eat the worms' offspring and are then consumed by other mantids, and the cycle repeats.

Now researchers may have discovered how the parasite pulls off its fatal trick: it seems to have evolved to use genes that its species once “stole” from the mantids themselves, enabling the worm to make proteins that affect the mantids' nervous system. If confirmed, these findings, published recently in *Current Biology*, would be the most extensive documented case of gene transfer between animal species.

Mantids infected with *C. fukuii* become attracted to light, like the shiny surface of water. This behavior is believed to arise from protein-level changes in both the parasite and the host's brain, says senior author Takuya Sato, a biologist at Japan's Kobe University. Because genes encode the instructions to build these proteins, Sato and his colleagues set out to examine how both species' gene activity changed during the course of a horsehair worm infection.

The team found that a whopping 1,420 of the parasite's genes resembled those of their hosts and that these genes were most active when the parasite was pulling the host's strings.

Genes can move from one living organism to another in a process called horizontal gene transfer, which is common in bacteria but rare between animals. “That would be very amazing—to have thousands of genes acquired by horizontal gene transfer from the host to parasites,” says Etienne Danchin, a biologist at France's Sophia Agrobiotech Institute, who was not involved with the research. “But I think they need to confirm this claim,” he says, because the researchers haven't yet located these potentially stolen genes in the worm's genome. The new study confirmed only that they were present in the parasite's tissue samples, and it is still possible that some of these genes were just contamination from the mantid, Danchin says.

“We should reserve judgment on the role and extent of horizontal gene transfer until a whole genome sequence is available that confirms that the transcripts are correctly attributed to the mantid and the worm,” says Julie Dunning Hotopp, a microbiologist at the University of Maryland Baltimore, who was not involved with the study.

Sato plans to check the parasites' genome next. “The mechanism of horizontal gene transfer in *C. fukuii* is still a huge mystery,” he says. “By investigating genomes of *C. fukuii* and its mantid host,” he hopes to get closer to unraveling it.

Darren Incorvaia is a writer and comedian based in Chicago. Follow him on Twitter @MegaDarren

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Evolution

- **Starfish Are Heads--Just Heads**
  Scientists have finally figured out how to make heads or tails of starfish

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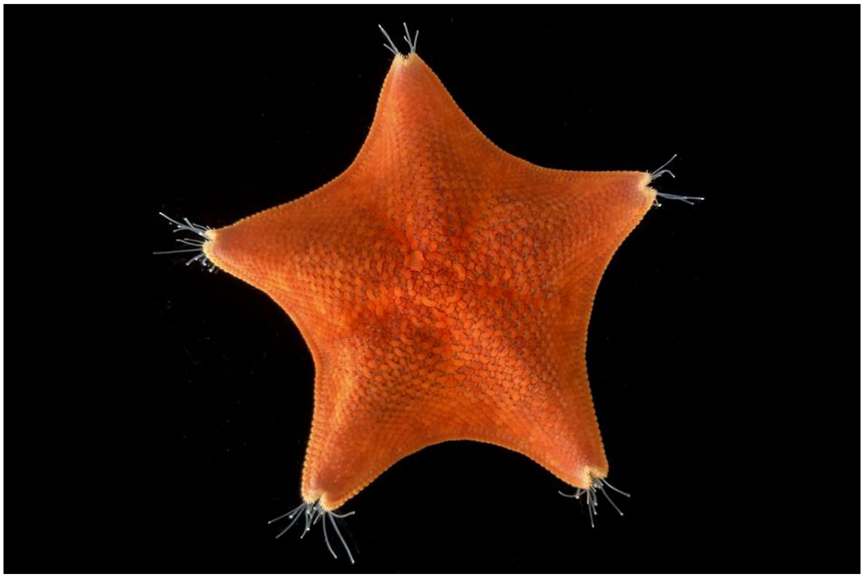
Starfish Are Heads—Just Heads

Scientists have finally figured out how to make heads or tails of starfish

By Lori Youmshajekian



The unusual five-axis symmetry of sea stars such as *Patiria miniata* has long confounded our understanding of animal evolution.
Laurent Formery

At first glance, starfish seem to be all limbs, with five appendages lined with rows of tube feet giving them their signature shape. Marine scientists have long wondered how they evolved to have such anatomy—and where their head might be.

It turns out that, genetically speaking, the animals are actually almost all head and no trunk, according to a new study published in *Nature*. The finding upends previous hypotheses about the body plans of starfish and is outright surprising, even to experts. "*They're all head?!*"wrote Gail Grabowsky, a professor of environmental science at the Chaminade University of Honolulu, who wasn't involved in the paper, in an e-mail to *Scientific American*. The results are "just super cool," she added. Plus, they offer clues about how these creatures became such bizarre evolutionary exceptions.

The vast majority of animals are bilaterally symmetrical, or bilaterian, meaning a single line can divide their body into two identical halves. But starfish—as well as sand dollars and sea anemones—have radial symmetry, with identical segments of their body radiating out from a central point. In particular, starfish, also called sea stars, have fivefold radial symmetry, so the animal can be divided into five identical segments.

A set of molecular markers on a sea star's genes determine the animal's body plan, which includes its radial symmetry and organ structure. These genetic networks exist in all bilaterian organisms. But somewhere in their evolution, sea stars appear to have shaped themselves in a completely new way, resulting in a "weird" body that seems to diverge from the bilateral norm, explains study co-author Chris Lowe, an evolutionary biologist at Stanford University.

The same genetic markers that tell cells and tissues to form a head in one species can result in different anatomy in other species. The more closely related the species, the more likely they are to use the same genes for the same anatomy. But for evolutionarily odd animals, scientists have a hard time figuring out which parts of the anatomy are the head versus the trunk versus the tail because it's not immediately obvious from how they look. Here, the term "head" broadly refers to the anterior of an animal. For some animals, that means a brain, but starfish don't have that organ. Instead the head genes are involved in the development of the starfish's nervous system and skin—features that are structurally different from a brain, even though they have the same genetic background.

To locate the parts of the starfish body where head-coding genes are active, the researchers compared the genetic markers in a small *Patiria miniata* sea star with *Saccoglossus kowalevskii,* a species of acorn worm that is closely related to starfish and that has a well-studied genome. Advances in laboratory techniques allowed the team to create a three-dimensional map of the genes that were expressed in thinly sliced samples of the starfish's arms.

The researchers found that the genes in the head region of the acorn worm were "switched on" in the starfish's bumpy skin, which covered its entire body. Those anterior genes were especially active at the center of each arm, whereas the genetic signatures became more posterior moving out toward the perimeter of each arm. And surprisingly, they entirely lacked the genetic patterning for a trunk, essentially the torso of an animal, says Lowe, whose work is funded by Chan Zuckerberg Biohub.

Basically, the starfish was all headlike. This contradicts textbook descriptions of echinoderms, the evolutionary group that includes starfish, as animals that have lost their head. This study shows that "rather than losing their head, they're almost entirely head, and they've actually lost their trunk," Lowe says.

"It's a really, really interesting piece of work," says Imran Rahman**,** a principal researcher at the Natural History Museum in London. "They've done a lot of careful analyses, and I found it very convincing."

The study begins to probe a bigger evolutionary question: How did the sea star and its equally-strange echinoderm siblings develop their unique starlike symmetry? “It is a big mystery how this animal really evolved this shape,” says Paola Oliveri, a professor in developmental and evolutionary biology at University College London, who was not involved in the study. Millions of years ago, animals in this phylum—including starfish, brittle stars, sea cucumbers and sea urchins—were all bilateral. Today their bilateral larvae develop into their familiar five-axis structure as they grow, meaning that at some point, starfish dismantled all the genetic mechanisms of their bilateral ancestors.

“They reformed [that body plan] in a completely novel way, which explains why they’re so weird,” says the study’s lead author Laurent Formery, a postdoctoral researcher at Lowe’s lab at Stanford. But why and how this change occurred remains a mystery.

Beyond just sea stars, the findings may help scientists understand how new animal shapes and structures evolve in other branches of the tree of life, Oliveri says. They open up important research avenues about “how these animals develop and how they make this weird shape,” she says.

Next, the researchers will look to ancient fossils to find earlier sea star structures—perhaps some with more trunk and tail markers—to track when exactly the trunk was lost. The researchers also want to prove that the other echinoderms are covered in headlike regions as well.

“There’s more that can still be done to really confirm that this pattern extends across the whole phylum,” Rahman says. “Further analyses looking at different living species would help to clarify that.”

A version of this article with the title “Heads Up!” was adapted for inclusion in the January 2024 issue of Scientific American.

Lori Youmshajekian is a freelance science journalist who reports on advances in health, environmental issues and scientific misconduct. She holds a master's degree in Science Journalism from New York University and has written for New Scientist, Yale E360, Retraction Watch and Medscape, among other outlets.

Genetics

- **Sperm Cell Powerhouses Contain Almost No DNA**
  Scientists discover why fathers usually don’t pass on their mitochondria’s genome

Sperm Cell Powerhouses Contain Almost No DNA

Scientists discover why fathers usually don’t pass on their mitochondria’s genome

By Sneha Khedkar

Mitochondria.
Kateryna Kon/Science Source

Almost every type of human cell is powered by mitochondria, bean-shaped organelles that use oxygen to synthesize usable energy.* These structures evolved billions of years ago from free-swimming bacteria that were engulfed by some of humanity's earliest ancestors. Because of this history, mitochondria still have their own ring-shaped DNA—completely separate from the 23 chromosomes that make up most of the human genome. And although those chromosomes come from both parents, nearly all humans inherit their mitochondrial DNA (mtDNA) from their mother's egg cell.

So what happens to the mtDNA in the sperm cell? Understanding this process is important for studying mitochondrial diseases, genetic disorders that result when these “powerhouses” don't function properly. Scientists know that molecular processes break down the sperm's mitochondria soon after fertilization in other animals—but no one has been able to pinpoint when this elimination happens in humans.

Now biologists have discovered that it happens early—in fact, human sperm's few mitochondria contain virtually no DNA at all. The findings were published in a recent issue of *Nature Genetics*. “We were very surprised by the absence of mtDNA in mature human sperm” because previous studies had produced conflicting results, says the study's senior author, molecular biologist Dmitry Temiakov of Thomas Jefferson University in Philadelphia. This mtDNA-elimination process might play a role in human infertility and can help science understand mitochondrial diseases, he says.

Using molecular biology and microscopy techniques, the researchers examined human sperm cells across their developmental stages. They showed that mitochondria in the sperm's precursor cells did contain DNA, along with an important protein called mitochondrial transcription factor A (TFAM) that maintains and protects that DNA. But when the sperm cells matured, a slight chemical change prevented TFAM from entering their mitochondria. Instead it entered the nucleus, where it could no longer prevent the mtDNA from degrading.

If mtDNA sticks around in sperm's mitochondria, it could become a source of infertility. Previous studies showed that people with decreased sperm counts and motility have elevated amounts of mtDNA in those cells.

Mouse studies have indicated that TFAM is absent in sperm's mitochondria, says Xinnan Wang, a mitochondrial cell biologist at the Stanford University School of Medicine. The new study, along with prior research in other animals that found paternal mtDNA can be eliminated after egg fertilization, “shows multiple mechanisms that may contribute to maternal mitochondrial inheritance in different organisms,” she says.

Temiakov says there are probably other, yet unidentified mechanisms that regulate mtDNA in different cells and that might contribute to mitochondrial diseases if disrupted. “We need to uncover these mechanisms,” he says, “to better understand mitochondrial diseases and how to treat them.”

**Editor’s Note (3/7/24): This sentence was edited after posting to correct the description of the human cells that are powered by mitochondria.*

Sneha Khedkar is a biologist-turned freelance science journalist from India with a passion for writing about science where it intersects with society. Follow her on Twitter @sneha_khedkar, and visit her website.

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Geology

- **Calling Our Times the 'Anthropocene Epoch' Matters Dearly to You**
  The name Anthropocene means human activity is profoundly changing our environment, and you’ll have to plan for those changes

Calling Our Times the ‘Anthropocene Epoch’ Matters Dearly to You

The name Anthropocene means human activity is profoundly changing our environment, and you’ll have to plan for those changes

By Naomi Oreskes

Canada's Crawford Lake has sediment layers that may show when human activity began to change our planet.
Peter Power/AFP via Getty Images

In 1922 British geologist Robert Lionel Sherlock published a book, *Man as a Geological Agent: An Account of His Action on Inanimate Nature*, that put forth what is now considered to be the central argument for recognizing the Anthropocene as a new geological epoch: the scale and character of human activities have become so great as to compete with natural geological and geophysical forces. More than 100 years later geologists have broadly rallied around Sherlock's core idea, and the Anthropocene Working Group—a committee of scientists (including me) who report to the International Commission on Stratigraphy—has proposed Crawford Lake in Canada as the official site for marking the Anthropocene.

Crawford Lake contains an exceptionally well-preserved sedimentological record of environmental history. Its annual layers of lake mud, meticulously studied by geologist Francine M. G. McCarthy of Brock University in Ontario, display the "golden spike" of radioactive plutonium produced in the mid-century by atmospheric atomic bomb tests, as well as ash from coal-fired power plants, heavy metals, and microplastics.

The 2023 Crawford Lake announcement attracted a great deal of press, much of it focused on a misguided controversy that erupted over how narrowly to define the Anthropocene. Amid this hubbub, observers may have been left to wonder why defining this chapter in Earth's history should matter to ordinary people at all.

Sherlock was not a maverick. He was a respected member of the British Geological Survey, and he built on the work of others who had already made similar arguments. One was American polymath George Perkins Marsh, who had called attention to deforestation and the role of humans as "disturbing agents." In addition to revisiting deforestation, Sherlock described the altered courses of rivers through dams and canals; changes to the hydrologic cycle and to the seacoast; and the huge quantities of stuff people move while mining the raw materials of modern civilization and building streets, bridges and railroads. Human impacts were becoming so manifest, Sherlock argued, that the distinction between "natural" and "artificial" was becoming difficult to sustain. We needed a new term—he suggested "anthropography"—to study the effects of human activities on Earth.

Sherlock closed his book with a chapter on climate change, in which he drew on the arguments of two prominent scientific colleagues. One was geochemist Svante Arrhenius, who is known today as the first person to calculate the potential impact of increased atmospheric carbon dioxide on climate. The other was American geologist Thomas Chrowder Chamberlin, who had proposed that the ice ages were caused by fluctuations in CO2 levels. Chamberlin, Sherlock explained, "thinks that the Permian glaciation was a consequence of the removal from the atmosphere of the vast mass of carbon locked up by animals and plants, in the forms of limestone and coal, during the carboniferous period." If that were so, then "we may reasonably consider the result of a reversal of the process," which was already underway: burning those vast coal deposits was putting the CO2 back into the atmosphere, which would warm the planet—an argument that was later taken up by American oceanographer Roger Revelle, a scientific mentor to former vice president Al Gore.

In the 1950s Revelle and other scientists began the sustained study of anthropogenic climate change, and in 2000 Eugene F. Stoermer and Paul J. Crutzen formally proposed the word "Anthropocene" in a paper to reflect the idea that profound, irreversible changes were taking place.

But science is intrinsically conservative—the burden of proof is always on those making a novel claim—and the social and economic consequences of recognizing the adverse effects of burning fossil fuels have led to tremendous resistance beyond the halls of scientific conferences and the pages of scientific journals.

The definition of the Anthropocene matters for at least two reasons. The first is that it is a way for scientists to declare—as loudly as they can while still behaving as scientists—that the shifts going on around us are no small issue. Anthropogenic climate change is far more than an "inconvenient truth"; it is a profound alteration in the conditions of life on Earth. In myriad ways—large and small—the past may no longer be a reliable guide to the future. When taken seriously, that means we must rethink core assumptions about how we build our economies and our infrastructures, how we travel, how we plan for global pandemics, and even how we eat.

The second reason is that the definition of the Anthropocene extends the conversation beyond climate change. What geologists can now see in rocks—from the subtle (think changes in the ratios of carbon and oxygen isotopes) to the gross (think plastic residues in marine sediments) points to large-scale, far-ranging and utterly pervasive human impacts.

It is common for people to say (or think) that as climate change proceeds, we can "just adapt." Some wealthy people even think that, if necessary, they will move to higher ground or higher latitudes (or, preposterously, to Mars).* No doubt some people will become climate refugees, either voluntarily or under duress. But the definition of the Anthropocene reminds us that the challenge we face is geological in scale. It affects the whole Earth. It reminds us that as this new epoch unfolds, there won't be anywhere to hide.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

**Editor's Note (3/18/24): This sentence was edited after posting to correct the description of where some people think they will move if necessary.*

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

2023).

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Health Care

- ## Now There Are Better Ways Than BMI Charts to Assess Health Risks

  The body mass index is flawed, and medicine now has better options to measure obesity

Now There Are Better Ways Than BMI Charts to Assess Health Risks

The body mass index is flawed, and medicine now has better options to measure obesity

By Lydia Denworth

Jay Bendt

According to standard calculations, my husband's body mass index (BMI) is too high. Yet he is the fittest person I know—an athlete carrying plenty of muscle and very little fat.

Therein lies the problem with BMI. Derived by dividing someone's weight in kilograms by the square of their height in meters, a BMI number classifies a person as underweight (less than 18.5), normal weight (18.5 to 24.9), overweight (25 to 29.9) or obese (30 or more). But that simple formula obscures critical details such as the difference between muscle and fat. When it comes to individual health risks, those details tell the real story.

The shortcomings of BMI have been recognized for decades. Yet physicians kept using it as a quick way to diagnose obesity and as a proxy for overall health. “It made life really easy,” says clinical psychologist Cynthia Bulik, founding director of the University of North Carolina Center of Excellence for Eating Disorders. “It also led to a type of tunnel vision.”

Equating a slightly high BMI with poor health isn't always accurate. The American Medical Association acknowledged as much when it announced last June that BMI alone is an imperfect measure and that clinical practice needs to change.

The new thinking on BMI does not negate the need to address the health risks associated with a high body-fat percentage. In 2013 the AMA recognized obesity as a disease and noted that it often leads to many dangerous conditions, including cancer, diabetes and heart disease. The risks of obesity haven't changed. For the time being, however, insurers still rely on BMI to determine people's eligibility for bariatric surgery and most weight-loss drugs, including popular new options such as Wegovy.

A recent study showed just how imprecise BMI can be. Yftach Gepner, a physiologist and epidemiologist at Tel Aviv University, and his colleagues looked at data on about 3,000 Israeli men and women. Roughly one third of those whose BMI placed them in the normal range were found to be obese when their actual body fat was measured. And a third of those who were identified as overweight by their BMI had normal amounts of body fat. “If you are combining the misclassification on both sides," Gepner says, using BMI to determine obesity "is like flipping a coin."

Not only does BMI fail to distinguish between muscle and fat, but it says nothing about where that fat sits in your body, says Priya Jaisinghani, an endocrinologist and specialist in obesity at N.Y.U. Langone Health in New York City. With fat, as with real estate, location matters. Abdominal fat confers higher risk, as does fat around vital organs. A 2018 study looked at magnetic resonance imaging scans—the gold standard for body-composition research—collected by the U.K. Biobank, a large biomedical database. The results showed that people with fat concentrated in their abdomen had higher risk for type 2 diabetes, heart disease and metabolic disease than did people with the same BMI and of the same age whose fat was spread through other parts of their body.

A further problem is that BMI is based on height and weight tables developed using data from non-Hispanic white people, mostly men. Yet researchers now know that race, ethnicity, sex and age affect body composition and health risks differently. For instance, Black people tend to have greater muscle mass and thus may be misclassified as obese on the basis of BMI. The opposite is true for Asians, who tend to have more body fat at lower BMIs, so their actual disease risks may be missed.

Although BMI has value for assessing obesity at a population level, better methods exist for individuals. "The key is not to use BMI on its own as an index of health," Bulik says. To properly assess health, doctors should combine the index with measures such as waist circumference, blood pressure and cholesterol levels. Bioelectrical impedance analysis, which uses electric signals to tell fat from muscle in the body, is becoming more common in medical offices. "In a very few years it is going to become standard," Gepner says. DEXA scans, a type of x-ray imaging that can distinguish between muscle and fat, and MRI also can be used to measure body fat, although they tend to be more costly and are therefore less accessible.

With so many alternatives available, no one, including health-care workers, should give BMI too much weight.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

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

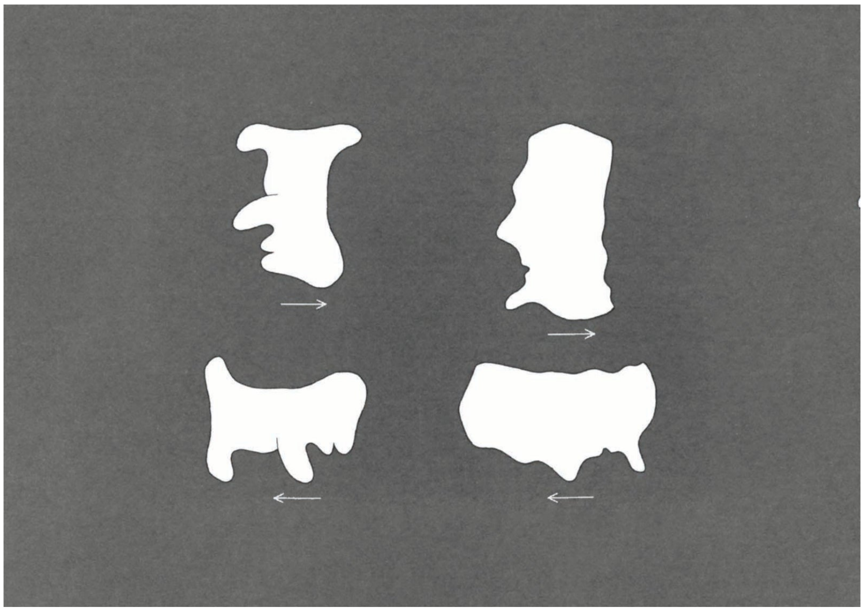
History

- **January 2024: Science History from 50, 100 and 150 Years Ago**
  Sleep potion; top speed limits

January 2024: Science History from 50, 100 and 150 Years Ago

Sleep potion; top speed limits

By Mark Fischetti



1974, Retina Trick: “Figure at top left can look like a person's head with a chef's hat or, when rotated 90 degrees, like a dog (*bottom left*). Figures at right can look like a bearded man's head or a U.S. map. When people tilted their head 90 degrees (*shown by arrow*) to view, they preferentially recognized the figure that was upright in the environment instead of the figure that was upright on the retina.”
Scientific American, Vol. 230, No. 1; January 1974

1974

Sleep Potion Boots Delta Waves

“Experiments dating back as far as 1913 have pointed toward a natural sleep potion in the body fluids of an animal that induces sleep when it is injected into another animal. Such a factor has now been partially characterized by a group at the University of Basel. They call it ‘sleep-factor delta’ because it promotes the production of delta waves, the long, slow brain waves characteristic of light sleep."

Scientists still consider sleep-factor delta, now called delta sleep-inducing peptide, to be a leading sleep regulator.

1924

Top Speed Limit: 35 Miles Per Hour

"Every state, almost, has a general speed limit on the open road. Some states name a figure not to be exceeded under any circumstances. Others set a figure related to reckless driving; if you drive faster than this and have a smash, it is up to you to prove that you were not reckless. Two states, Maine and Maryland, have both: more than 25 miles per hour establishes *prima facie* evidence against the driver, and more than 35 is categorically prohibited. In all other states, the driver has to read the book to discover whether the speed limit is absolute or *prima facie*. Five states specify 25 miles, sixteen name 30, and nine 35. As extremes, we have 20 in Massachusetts and 40 in Kansas. Three states ask for a 'reasonable and proper' speed, without stating any numerical limits. In overtaking a car ahead, the faster we move and the quicker we get it over with, the less road is it necessary for us to preempt. So Virginia requires that an illegal speed can be maintained for an eighth of a mile before it becomes an offense; Delaware, Massachusetts, Minnesota and New Hampshire give the driver a quarter-mile grace; while Florida, Louisiana and Missouri allow a driver to burn up the road for a half-mile before the speed becomes a matter for police interference."

Chunnel Plan

"The English Channel tunnel project is kept alive by its promoters, although the British government persists in refusing to grant the necessary authority, for national and strategic reasons. The material to be encountered for the entire distance is very favorable, being a deep bed of chalk infiltrated with clay. With the boring machine designed for this work, a heading 12 feet in diameter can be driven at 120 feet per day, and two machines started at opposite ends should meet in less than three years. Completion of the concrete-lined tunnel is estimated at 4½ years. With present prices the cost is estimated at $145,000,000."

Plans for a tunnel were made numerous times beginning in 1802, but one was never achieved until 1994, when Eurotunnel, now Getlink, opened the Channel Tunnel, quickly dubbed the Chunnel.

1874

My Farmland for Your Magazines

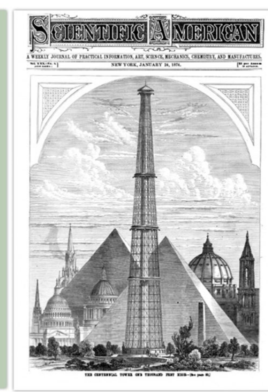
"One of our esteemed subscribers says that he has taken the *Scientific American* regularly for the past 25 years, and has the volumes all bound. He was recently offered a farm of 160 acres of land, free and clear, in exchange for these volumes, but declined the trade. He has derived great benefit from the volumes, and holds them to be of more value to him than many hundred acres of farming land."

Not Dead Yet

“The late Marquis d'Ourche, one of whose friends was buried alive, left a sum of 20,000 francs ($4,000) to the French Academy of Medicine, to be given to the inventor of a simple process of ascertaining when death has really occurred, and a further sum of 5,000 francs for discovery of a scientific method of verifying death. Altogether 102 essays were sent in. Most contained such absurd suggestions that the list was cut to 32. The large prize was not awarded, but the 5,000 francs were divided between four competitors. No new facts, likely to enlarge the domain of forensic medicine, have been elucidated by these investigations.”

Marshmallow Plates

“Gypsum mixed with 4 percent of powdered marshmallow root will harden in about one hour, and can then be sawn or turned, and made into dominoes, dice and so on. With 8 percent of marshmallow, the hardness of the mass is increased, and it can be rolled out into thin plates, and painted or polished.”



Mark Fischetti has been a senior editor at *Scientific American* for 17 years and has covered sustainability issues, including climate, weather, environment, energy, food, water, biodiversity, population, and more. He assigns and edits feature articles, commentaries and news by journalists and scientists and also writes in those formats. He edits History, the magazine's department looking at science advances throughout time. He was founding managing editor of two spinoff magazines: *Scientific American Mind* and *Scientific American Earth 3.0*. His 2001 freelance article for the magazine, "Drowning New Orleans," predicted the widespread disaster that a storm like Hurricane Katrina would impose on the city. His video *What Happens to Your Body after You Die?*, has more than 12 million views on YouTube. Fischetti has written freelance articles for the *New York Times, Sports Illustrated, Smithsonian, Technology Review, Fast Company,* and many others. He co-authored the book *Weaving the Web* with Tim Berners-Lee, inventor of the World Wide Web, which tells the real story of how the Web was created. He also co-authored *The New Killer Diseases* with microbiologist Elinor Levy. Fischetti is a former managing editor of *IEEE Spectrum Magazine* and of

Family Business Magazine. He has a physics degree and has twice served as the Attaway Fellow in Civic Culture at Centenary College of Louisiana, which awarded him an honorary doctorate. In 2021 he received the American Geophysical Union's Robert C. Cowen Award for Sustained Achievement in Science Journalism, which celebrates a career of outstanding reporting on the Earth and space sciences. He has appeared on NBC's Meet the Press, CNN, the History Channel, NPR News and many news radio stations. Follow Fischetti on X (formerly Twitter) @markfischetti

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Mathematics

- ## The Gambling Strategy That's Guaranteed to Make Money and Why You Should Never Use It
  The martingale betting strategy has led many gamblers to ruin when the Kelly criterion could have brought them riches

The Gambling Strategy That’s Guaranteed to Make Money and Why You Should Never Use It

The martingale betting strategy has led many gamblers to ruin when the Kelly criterion could have brought them riches

By Jack Murtagh

Pictures Colour Library/Alamy Stock Photo

Beneath the varnish of flashing lights and free cocktails, casinos stand on a bedrock of mathematics, engineered to slowly bleed their patrons of cash. For years mathematically inclined minds have tried to turn the tables by harnessing their knowledge of probability and game theory to exploit weaknesses in a rigged system.

An amusing example played out when the American Physical Society held a conference in Las Vegas in 1986, and a local newspaper reportedly ran the headline “Physicists in Town, Lowest Casino Take Ever.” The story goes that the physicists knew the optimal strategy to outwit any casino game: don't play.

Despite the warranted pessimism about beating casinos at their own games, a simple betting system based in probability will, in theory, make you money in the long run—with a huge caveat.

On supporting science journalism

Consider betting on red or black at the roulette table. The payout is even. (That means if you bet $1 and win, you win $1. But if you lose, you lose your $1.) And, for simplicity, assume that you really have a 50–50 shot of calling the correct color. (Real roulette tables have some additional green pockets on which you lose, giving the house a slight edge.) We'll also suppose that the table has no maximum bet.

Here's the strategy: Bet $1 on either color, and if you lose, double your bet and play again. Continue doubling ($1, $2, $4, $8, $16, and so on) until you win. For example, if you lose the first two bets of $1 and $2 but win your third bet of $4, that means you lose a total of $3 but recoup it on your win—plus an additional $1 profit. And if you first win on your fourth bet, then you lose a total of $7 ($1 + $2 + $4) but make out with a $1 profit by winning $8. This pattern continues and always nets you a dollar when you win. If $1 seems like a measly haul, you can magnify it by either repeating the strategy afresh multiple times or beginning with a higher initial stake. If you start with $1,000, double to $2,000, and so on, then you will win $1,000.

You might object that this strategy makes money only if you eventually call the right color in roulette, whereas I promised *guaranteed* profit. The chance that your color will hit at some point in the long run, however, is, well, 100 percent. That is to say, the probability that you'll lose every bet goes to zero as the number of rounds increases. This holds even in the more realistic setting where the house enjoys a consistent edge. If there is at least some chance that you'll win, then you will win eventually because the ball can't land in the wrong color forever.

So should we all empty our piggy banks and road-trip to Reno, Nev.? Unfortunately, no. This strategy, called the martingale betting system, was particularly popular in 18th-century Europe, and it still draws in bettors with its simplicity and promise of riches—but it is flawed. Gambling ranked among the many vices of notorious lothario Jacques Casanova de Seingalt, and in his memoirs he wrote, “I still played on the martingale, but with such bad luck that I was soon left without a sequin.”

Do you spot a flaw in the profit-promising reasoning above? Say you have $7 in your pocket, and you'd like to turn it into $8. You can afford to lose the first three bets in a row of $1, $2 and $4. It's not very likely that you will lose three in a row, though, because the probability is only one in eight. So one eighth (or 12.5 percent) of the time you'll lose all $7, and the remaining seven eighths of the time you'll gain $1. These outcomes cancel each other out: $-1/8 \times \$7 + 7/8 \times \$1 = \$0$.

This effect scales up to any amount of starting capital: there is a large chance of gaining a little bit of money and a small chance of losing all your money. As a result, many gamblers will turn a small profit playing the martingale system, but the rare gambler will suffer complete losses. These forces balance out so that if a lot of players used the strategy, their many small winnings and few huge losses would average out to $0.

But the true argument doesn't stop at $7. As I mentioned, the idea is to keep playing until you win. If you lose three in a row, go to the ATM and bet $8 on a fresh spin. The guaranteed profit depends on a willingness to keep betting more—and the inevitability of winning at some point with persistent play.

Here's the key defect: you have only so much money. The amount you wager each round grows exponentially, so it won't take long before you're betting the farm just to make up your losses. It's a bad strategy for generating wealth when you're taking a small but nonzero chance of risking your livelihood for a puny dollar. Eventually you'll go bankrupt, and if this happens before your jackpot, then you'll be out of luck.

Finitude breaks the martingale in another way, too. Probability dictates that you are guaranteed to win *eventually*, but even if you had a bottomless purse, you could die before “eventually” arrived. Yet again the pesky practicalities of the real world meddle with our idealized fun.

As we reflect back, it might seem obvious that you can't actually force an advantage in a casino game. Yet it *is* surprising that we have to resort to arguments about solvency and mortality to rule it out. The dreamy pencil-and-paper world that mathematicians inhabit, where we can roam freely across all of infinity, permits what should be impossible.

For games with winning chances of 50 percent or worse, there is no betting strategy that secures an upper hand in a finite world. What about more favorable games? If you had $25 in your wallet and could repeatedly bet on the outcome of a biased coin that you knew turned up heads 60 percent of the time (where you would again either lose your full bet or gain an amount equal to it), how much money could you turn your $25 into? Researchers tested 61 finance students and young professionals with this exact experiment, letting them play for half an hour, and were surprised by their poor performance. (You can try it for yourself.)

A disconcerting 28 percent of participants went broke despite having an advantage, and a shocking two thirds bet on tails at some point in the game, which is never rational. On average, the participants walked away with $91 (winnings were capped at $250). This might seem like an ample take for someone starting with $25, but the researchers calculated that over the 300 coin tosses time allowed for, the average winnings of players using the *optimal* strategy (described below) would be more than $3 million!

The players face a dilemma: Bet too much per round, and they risk losing their entire bankroll on a few unlucky tosses. But bet too little, and they fail to capitalize on the sizable advantage the biased coin affords them. The Kelly criterion is a formula that balances these rival forces and maximizes wealth in such situations. Scientist John Kelly, Jr., who worked at Bell Labs in the mid-20th century, realized that to make the most money, a gambler should bet a consistent fraction of their purse on every round.

He worked out a simple formula for the perfect fraction, which he described in a 1956 paper: $2p - 1$, where p is the probability that you'll win ($p = 0.6$ in the coin-flip example). In the experiment, betting 20 percent of your available cash on each flip hits the sweet spot. Note that the strategy puts more money on the line if you keep winning, and it constricts bet size as your cash dwindles, making it very unlikely that you'll go bust.

Unlike the martingale betting strategy, the Kelly criterion works in practice and proves its worth as a mainstay of quantitative finance. Professional card counters in blackjack also use it to size their bets when the deck gets hot.

Economists warn that although the Kelly criterion works for generating wealth, it's still a gamble with pitfalls of its own. For one, it assumes that you know your probability of winning a bet, which can be true in many casino games but less so in fuzzy domains such as the stock market. Also, Kelly asserts that in the coin-toss experiment, you're most likely to grow your wealth if you keep betting 20 percent of it. But if you have $1 million to your name, it's perfectly reasonable not to want to gamble $200,000 on a coin flip. At some point, you will need to price in your personal level of risk aversion and adjust your fiscal decisions to respect your own preferences.

Still, if you find yourself placing wagers with odds in your favor, ditch the martingale and remember that the Kelly criterion is a better bet.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

Jack Murtagh is a freelance math writer and puzzle creator. He writes a column on mathematical curiosities for *Scientific American* and creates daily puzzles for the Morning Brew newsletter. He holds a Ph.D. in theoretical computer science from Harvard University. Follow Jack on X @JackPMurtagh

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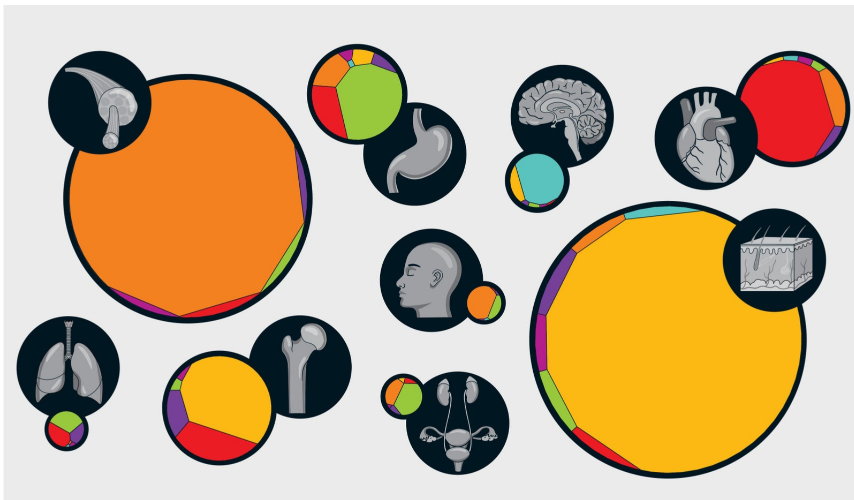
Microbiology

- **See Your Body's Cells in Size and Number**
  The larger a cell type is, the rarer it is in the body—and vice versa—a new study shows

See Your Body’s Cells in Size and Number

The larger a cell type is, the rarer it is in the body—and vice versa—a new study shows

By Clara Moskowitz, Jen Christiansen & Ni-ka Ford



Ni-ka Ford and Jen Christiansen

Many aspects of our world, from the body mass of creatures in the animal kingdom to the population of cities across the globe, follow an intriguing mathematical pattern. Known as Zipf's law, the rule says that when something's size is doubled, that thing becomes about half as common. Researchers wondered whether the law extended to the human body. Ecologist Ian A. Hatton of McGill University, independent researcher Jeffery A. Shander and their colleagues amassed data about the volume and frequency of human cells and looked for the pattern. It turns out that it holds.

“As you double the volume of a cell, the frequency of cells of that size is halved,” Hatton says. Teensy, nonnucleated red blood cells are by far the most common cells in our bodies, whereas the comparatively gigantic muscle cells in our arms and legs are the scarcest. Being able to use a cell's size to estimate its frequency in the body could help doctors better understand certain body systems and hard-to-count cell types, the researchers say. The study suggests, for instance, that immune cells called lymphocytes are far more common than biologists realized.

Credit: Ni-ka Ford (*illustrations*) and Jen Christiansen (*chart*); "The Human Cell Count and Size Distribution," by Ian A. Hatton et al., in *PNAS*, Vol. 120; September 2023 (*data*)

On supporting science journalism

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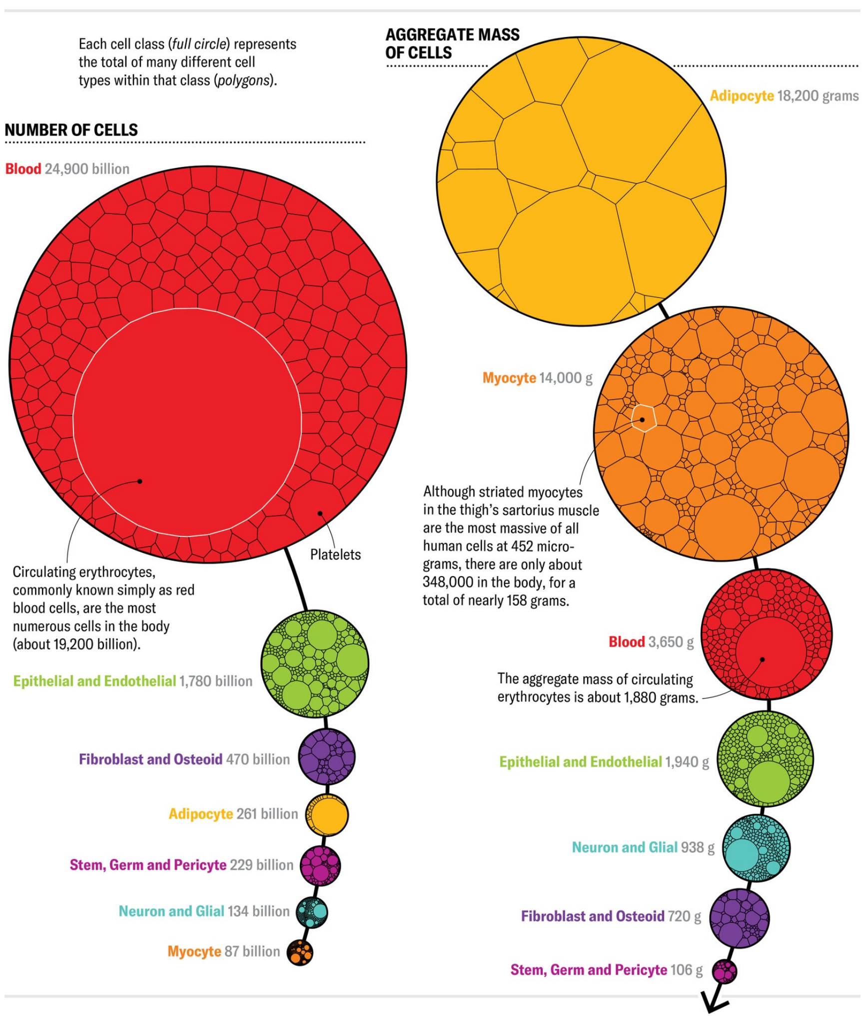
NUMBER AND AGGREGATE MASS OF CELLS IN THE HUMAN BODY, BY CELL CLASS

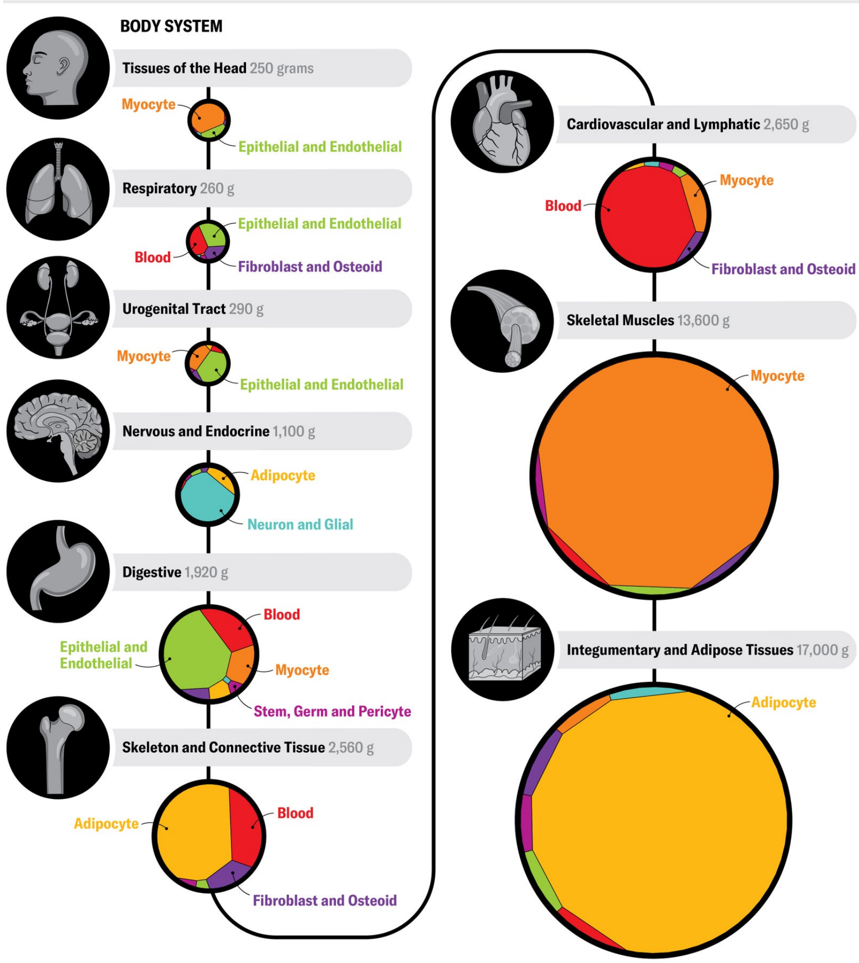
(Calculated for a 60-kilogram female form.) These two strands show the hierarchy of cells by number (frequency in the body) as well as by how much total biomass they account for in the body. The discrepancy between the two arises from the fact that the most numerous cells are often very small and therefore contribute only a modest amount of biomass, whereas the more massive cells, though relatively uncommon, make up much of our heft. Total cell mass does not equal total body mass, because bodies also include large volumes of water.



Credit: Jen Christiansen; "The Human Cell Count and Size Distribution," by Ian A. Hatton et al., in *PNAS*, Vol. 120; September 2023 (*data*)

MASS OF BODY SYSTEMS

(Calculated for a 60-kilogram female form.) Different systems in the human body account for differing amounts of our total biomass. The largest system, the integumentary and adipose tissues, consists mainly of skin and fat.



Credit: Ni-ka Ford (*illustrations*) and Jen Christiansen (*chart*); "The Human Cell Count and Size Distribution," by Ian A. Hatton et al., in *PNAS*, Vol. 120; September 2023 (*data*)

Clara Moskowitz is a senior editor at *Scientific American*, where she covers astronomy, space, physics and mathematics. She has been at *Scientific American* for a decade; previously she worked at Space.com. Moskowitz has reported live from rocket launches, space shuttle liftoffs and landings, suborbital spaceflight training, mountaintop observatories, and more. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science communication from the University of California, Santa Cruz.

Jen Christiansen is author of the book *Building Science Graphics: An Illustrated Guide to Communicating Science through Diagrams and Visualizations* (CRC Press) and senior graphics editor at *Scientific American*, where she art directs and produces illustrated explanatory diagrams and data visualizations. In 1996 she began her publishing career in New York City at *Scientific American*. Subsequently she moved to Washington, D.C., to join the staff of *National Geographic* (first as an assistant art director–researcher hybrid and then as a designer), spent four years as a freelance science communicator and returned to *Scientific American* in 2007. Christiansen presents and writes on topics ranging from reconciling her love for art and science to her quest to learn more about the pulsar chart on the cover of Joy Division's album *Unknown Pleasures*. She holds a graduate

certificate in science communication from the University of California, Santa Cruz, and a B.A. in geology and studio art from Smith College. Follow Christiansen on Bluesky @christiansenjen.bsky.social

Ni-ka Ford is a Certified Medical Illustrator who creates didactic illustrations and 3D visualizations for scientific research, journal publications, medical education, and patient educational materials. Her work can be found at www.enlightvisuals.com.

Neuroscience

- **Ping-Pong Ball Insulators Can Block Noise**
  Researchers harness acoustics principles to seal out noise pollution

| Next section | Main menu | Previous section |

Ping-Pong Ball Insulators Can Block Noise

Researchers harness acoustics principles to seal out noise pollution

By Rachel Berkowitz

Thomas Fuchs

Constant city noise has been linked to long-term health problems, but it's hard to keep out of homes and businesses; low-frequency sounds such as traffic and construction propagate easily through walls and other solid materials. Expensive, specialized paneling can help, but a new study in the *Journal of Applied Physics* shows how everyday materials and clever physics can also do the trick, creating a kind of sound insulator from strategically pin-pricked ping-pong balls.

Robine Sabat, an acoustics researcher at the University of Lille in France, has been trying to improve noise insulation by studying how sound waves bounce around in hollow cavities. When a sound wave passes over an opening in such a space, the wave squeezes and releases the air inside. This makes the air vibrate at a particular frequency depending on the cavity's size, shape and any holes it might have (just as blowing across a bottle's lip causes a hum, with the pitch depending on bottle size). And if cavities are constructed in just the right way, the bouncing sound waves inside will cancel one another out, dampening the noise.

Sabat chose ping-pong balls as a low-cost option with geometric properties that create resonance in the right low-frequency range. By drilling five holes in each ball, her team turned them into resonant cavities that each filter one frequency band out of the surrounding noise.

But combining the resonating balls to dampen large ranges of sound is tricky because the sound waves interact and affect which frequencies get dampened. To find the right arrangement, the researchers placed microphones inside two balls and adjusted the holes' positions and sizes until the combination captured multiple frequency bands. They added and adjusted more balls until the structure absorbed a wide range of frequencies.

“Getting the holes aligned perfectly took some practice,” Sabat says. Her team's arrangement of 90 balls, fixed to a sheet of plexiglass, reduced low-frequency sounds heard on the other side by up to 50 percent compared with the plexiglass surface alone.

“The design gives excellent sound attenuation, even below 500 hertz” (the range most associated with long-term health effects), says Olga Umnova, an acoustics researcher at the University of

Salford in England, who was not involved in the new study. She adds that a systematic, real-world comparison with simpler options, such as plexiglass sheets separated by an air gap, would be an important next step. Computer simulations have estimated that the ping-pong paneling improves sound reduction by 30 percent compared with an air gap alone.

Sabat's team hopes low-tech adjustments to the new technique could also help with other acoustic aims, such as focusing sound waves to improve sound quality in concert halls.

Rachel Berkowitz is a freelance science writer and a corresponding editor for *Physics Magazine*. She is based in Vancouver, British Columbia, and Eastsound, Wash.

Paleontology

- **Fossils Finally Reveal Fiery Colors of Prehistoric Animals**
  An ancient frog, bird and dinosaur wore elusive yellow and orange shades, a new lab technique reveals

Fossils Finally Reveal Fiery Colors of Prehistoric Animals

An ancient frog, bird and dinosaur wore elusive yellow and orange shades, a new lab technique reveals

By Riley Black

The bird *Confuciusornis*, which lived more than 120 million years ago, had warm-colored feathers.
Millard H. Sharp/Science Source

The prehistoric animal kingdom was a riot of colors, from iridescent-feathered dinosaurs to jet-black ink excreted by Jurassic squid relatives. Like modern-day animals, ancient species' hues helped them communicate, camouflage and even regulate body temperature. But reconstructing these colors today is a challenge because compounds and structures that color animals' skin, fur and feathers usually degrade or change during fossilization. Experts have developed methods to reliably detect structures and pigments related to dark colors like the black and brown of feathered dinosaurs, but other shades (like the yellow and reddish-orange made by pigments called pheomelanins) have been especially hard to pin down.

Now a team of scientists has filled in that missing chunk of the prehistoric palette by developing the first reliable test to detect these gingery colors in fossils. “Pheomelanin is clearly an elusive pigment, and these findings will absolutely help us to detect evidence of ginger pigments in other fossils,” says the study's lead author Tiffany Slater, a paleobiologist at University College Cork in Ireland. The results were recently published in *Nature Communications.*

Slater and her colleagues went looking for ginger shades in the fossil record because evidence of pheomelanins has shown up there far less often than the researchers expected, compared with modern-day animals. And the previously reported evidence was largely inconclusive. Scientists who interpreted a reddish color for the armored dinosaur *Borealopelta*, for example, couldn't distinguish whether the pheomelanin they found came from the original pigment or from contamination after the dinosaur's death.

So Slater and her co-authors created a test to distinguish between true chemical traces of ginger colors and those introduced by nonbiological sources. They heated various modern-day bird feathers in an oven to mimic the breakdown of biological compounds during the fossilization process. By inspecting the heated feathers under a microscope and using a chemical assay to identify different types of melanin, the team found that biological pigments do leave a distinct and identifiable signature in fossils. The researchers then checked various fossils for the chemical markers of the pigment and found them in a 10-million-year-old frog, the Cretaceous bird *Confuciusornis* and the dinosaur *Sinornithosaurus.*

The new analysis technique offers a “more accurate determination” of the colors of fossilized animals, says Liliana D'Alba, an evolutionary biologist at the Naturalis Biodiversity Center in the Netherlands, who was not involved in the new study. For example, flying pterosaurs are presumed to have been brightly colored but have not been examined in detail.

Further research might even reveal how ginger hues evolved in the first place. “Scientists still don't know how, or why, pheomelanin evolved,” Slater says, especially because its production can cause cancer in an animal's tissues. “The fossil record might just unlock the mystery.”

Riley Black, who formerly wrote under the name Brian Switek, is the author of *Skeleton Keys* and *My Beloved Brontosaurus*. She lives in Salt Lake City, Utah. Follow her on Twitter @Laelaps and on Instagram @laelaps

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Psychology

- ## To Lead a Meaningful Life, Become Your Own Hero
  From Gilgamesh to Star Wars, the narrative blueprint underpinning many heroic tales can offer a powerful way to reframe experiences

To Lead a Meaningful Life, Become Your Own Hero

From Gilgamesh to Star Wars, the narrative blueprint underpinning many heroic tales can offer a powerful way to reframe experiences

By Ben Rogers, Kurt Gray & Mike Christian

lerbank/Getty Images

What do *Beowulf, Batman* and *Barbie* all have in common? Many ancient legends, comic book sagas and blockbuster movies share a storytelling blueprint called the hero's journey. This timeless narrative structure, first described by mythologist Joseph Campbell in 1949, is found in ancient epics, such as the *Odyssey* and the *Epic of Gilgamesh*, and modern favorites, including the Harry Potter, *Star Wars* and *Lord of the Rings* series. Many such stories have become cultural touchstones that influence how people think about their world and themselves.

Our research reveals that the hero's journey is not just for legends and superheroes. In a recent study published in the *Journal of*

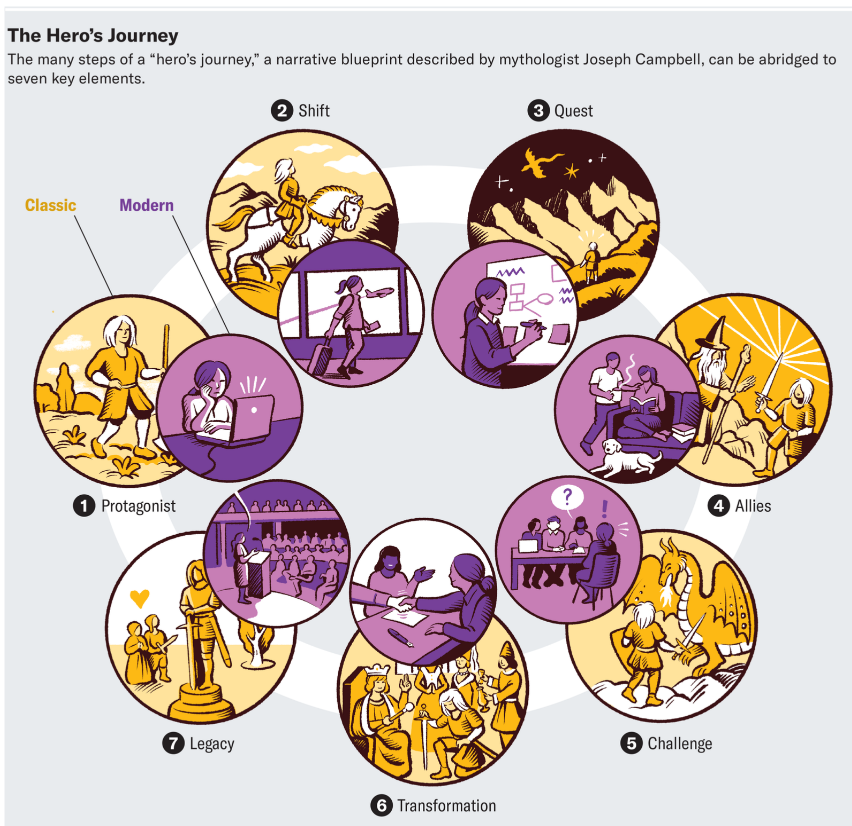
Personality and Social Psychology, we show that people who frame their own life as a hero's journey find more significance in it. This insight led us to develop a “restorying” intervention to enrich individuals' sense of meaning and well-being. When people start to see their own lives as heroic quests, we discovered, they report less depression and can cope better with challenges.

The human brain seems hardwired to make sense of the world through stories. Over millennia of evolution, *Homo sapiens* has spent countless hours sitting around fires and telling tales of challenge and triumph. Our interest in storytelling explains why we read magazine articles that open with an anecdote and why we naturally frame our lives in story form. These life tales stitch together different events into an overarching narrative with the storyteller as the protagonist. They help people define themselves and make existence more coherent.

Of course, some stories are better than others—some evoke awe and excitement, whereas others make people yawn. We wondered whether the hero's journey provides a template for telling a more compelling version of one's own history. After all, the hero's journey lies at the heart of the most culturally significant stories around the world.

To explore the connection between people's life stories and the hero's journey, we first had to simplify the storytelling arc from

Campbell's original formulation, which features 17 steps. Some of the steps in the original set are very specific, such as undertaking a "magic flight" after completing a quest. Think of Dorothy, in the novel *The Wonderful Wizard of Oz*, being carried by flying monkeys to the Emerald City after vanquishing the Wicked Witch of the West. Others are out of touch with contemporary culture, such as encountering "women as temptresses." We abridged and condensed the 17 steps into seven elements that can be found in both legends and everyday life: a lead protagonist, a shift of circumstances, a quest, allies, a challenge, a personal transformation and a resulting legacy.



Credit: Matteo Farinella; Source: Reference figure by Kevin House in "Seeing Your Life Story as a Hero's Journey Increases Meaning in Life," by Benjamin A. Rogers et al., in *Journal of Personality and Social Psychology*, Vol. 125, No. 4; October 2023

For example, in J.R.R. Tolkien's *The Lord of the Rings*, Frodo (the protagonist) leaves his home in the Shire (a shift) to destroy the Ring (a quest). Sam and Gandalf (his allies) help him face the enemy forces of Sauron (a challenge). He discovers unexpected inner strength (a transformation) and eventually returns home to help the friends he left behind (a legacy). In an everyday-life parallel, a young woman (the protagonist) might move to Los Angeles (a shift), develop an idea for a new business (a quest), get support from her family and friends (her allies), overcome self-doubt after initial failure (a challenge), grow into a confident and successful leader (a transformation), and ultimately help her community (a legacy).

With our condensed version of the hero's journey, we looked at the connection between how people told their life stories and their feelings of meaning in life. Across four separate studies, we collected life stories from more than 1,200 people, including online participants and a group of middle-aged adults in Chicago. We also used questionnaires to measure the participants' sense of meaning in life, amount of life satisfaction and level of depression.

We then examined their stories for the seven elements of the hero's journey. We found that people who had more of the elements in their life stories reported more meaning in life, more flourishing and less depression. These “heroic” people (men and women were equally likely to see their life as a hero's journey) reported a clearer sense of self than other participants did, as well as more new adventures, strong goals, good friends, and so on.

We also found that narratives in line with the hero's journey provided more benefits than other kinds, including a basic “redemptive” arc, in which a person's life story goes from defeat to triumph. Of course, redemption is often a part of the “transformation” aspect of the hero's journey, but compared with people whose life story contained only the redemptive narrative, those with a full hero's journey reported more meaning in life.

We then wondered whether making one's story more “heroic” would increase feelings of meaningfulness. We developed a “restorying” intervention in which we prompted people to retell their story as a hero's journey. Participants identified each of the seven elements in their life, and then we encouraged them to weave these pieces together into a coherent narrative.

In six studies with more than 1,700 participants, we confirmed that this restorying intervention worked: it helped people see their life as a hero's journey, which in turn made that life feel more meaningful. Intervention recipients also reported greater well-being and became more resilient in the face of personal challenges; these participants saw obstacles more positively and dealt with them more creatively.

Critically, our intervention required two steps: identifying the seven elements and connecting them in a coherent story. In other studies, we found that doing only one or the other—such as describing aspects of one's life that resembled the hero's journey without linking them together—had a much more modest effect on feelings of meaning in life than doing both.

Furthermore, the intervention increased participants' tendency to perceive more meaning in general. For instance, after retelling their stories according to our prompts, people were more likely to perceive patterns in seemingly random strings of letters on a computer screen.

Anyone can frame their life as a hero's journey—and we suspect that people can also benefit from taking small steps toward a more heroic life. You can see yourself as a heroic protagonist, for example, by identifying your values and keeping them top of mind in your day-to-day. You can lean into friendships and new experiences. You can set goals much like those of classic quests to stay motivated and challenge yourself to improve your skills. You can also take stock of lessons learned and ways you might leave a positive legacy for your community or loved ones.

Although you might never save the world on a massive scale, you could save yourself. You can become a hero in the context of your own life, which, at the very least, will make for a better story.

Are you a scientist who specializes in neuroscience, cognitive science or psychology? And have you read a recent peer-reviewed paper that you would like to write about for Mind Matters? Please send suggestions to Scientific American's *Mind Matters editor Daisy Yuhas at pitchmindmatters@gmail.com.*

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

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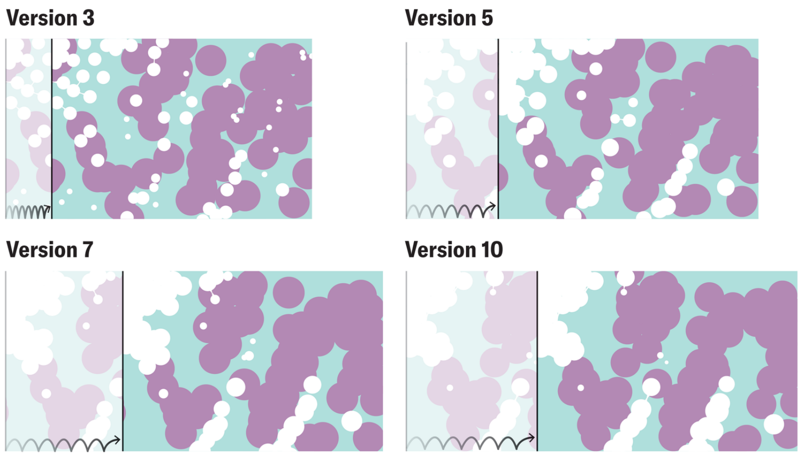
Robotics

- **Computers Sculpt Hopping Gelatinous Robots**
  These bloblike bots have been optimized for speed

Computers Sculpt Hopping Gelatinous Robots

These bloblike bots have been optimized for speed

By Matthew Hutson



Amanda Montañez

Most robots are designed by human engineers, who must painstakingly arrange every joint and artificial muscle to make the bot accomplish a specific task. The process is slow and limited by human imagination; having an algorithm do it instead could "help usher in the world of bespoke robotics," says computer scientist Josh Bongard of the University of Vermont. In a new study, he and his colleagues used feedback-based algorithms to design a variety of bloblike walking robots in record time. The results were published recently in the *Proceedings of the National Academy of Sciences USA*.

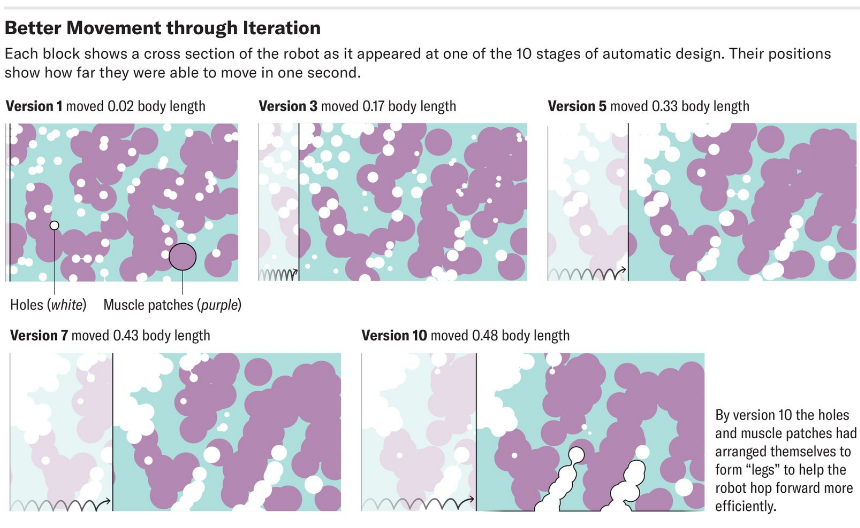
Each robot began as a digitally simulated brick of a gelatinous substance with 64 holes randomly interspersed throughout, like a block of Swiss cheese. It also contained 64 randomly placed artificial muscle patches that, when flexed, caused nearby parts of its body to stretch and constrict. At first, the simulated block simply jumped in place. But as the algorithm tweaked the muscle locations, as well as the holes' locations and sizes, the block began to hop forward. Nine versions later the holes had coalesced to sculpt a few stubby “legs,” which had become lined with muscle. The resulting digital bot could travel half its body length each second—and the entire design process, which the team repeated 100 times, took just 30 seconds on a laptop.

“The big contribution is the way they achieve all this in a very short time, with a very limited number of iterations,” says Cecilia Laschi, a mechanical engineer at the National University of Singapore, who studies soft robots but was not involved in the new study.

The researchers cast one of the designs in silicone, making a physical creature about half the size of a bar of soap. For muscles, the scientists affixed tiny bladders that could be flexed by pumping in pulses of air. The robot walked slower than the simulation—half a body length per minute—but significantly faster than a random design.

These movement-maximizing adjustments were guided by a type of optimization algorithm called gradient descent. This technique, which powers most machine-learning algorithms, finds optimal solutions to problems with an unwieldy number of variables. In this case, those variables were muscle locations, as well as hole locations and sizes. The algorithm repeatedly modified them strategically so the system improved with each iteration.

The team used the same technique to design virtual bots with other aims, such as transporting or launching an object. Next they hope to create more sophisticated machines that use sensors to interact with the world.



Credit: Amanda Montañez; Source: "Efficient Automatic Design of Robots," by David Matthews et al., in *Proceedings of the National Academy of Sciences USA*, Vol. 120; October 3, 2023

Matthew Hutson is a freelance science writer based in New York City and author of *The 7 Laws of Magical Thinking*.

Space Exploration

- **Here's How to Bring Mars Down to Earth: Let NASA Do What NASA Does Best**
  Increasing NASA's budget would ease pressure and allow it to dream even bigger

Here's How to Bring Mars Down to Earth: Let NASA Do What NASA Does Best

Increasing NASA's budget would ease pressure and allow it to dream even bigger

By Phil Plait

A Mars vista captured by NASA's Perseverance rover in April 2023.
NASA/JPL-Caltech/ASU/MSSS

NASA has a planet-size problem on its hands. Ironically, its source is here on Earth: Congress, which has the penny-wise but pound-foolish policy of releasing just a trickle of funding to the space agency every year, hobbles many of NASA's mission goals that require thinking past a two-year House or six-year Senate term. This hurdle has repercussions that can be felt across the solar system.

Right now on Mars the Perseverance rover is collecting small samples from inside the 45-kilometer-wide Jezero Crater, which held a huge lake billions of years ago. Scientists consider it one of the best places to scout for evidence of ancient life on Mars or at least to see whether conditions were ripe for its genesis.

These Martian souvenirs safely rest inside hermetically sealed cylinders that are either stored onboard the rover or dropped in strategic locations on the planet's surface. A future Mars-bound mission will pick them up and bring them to Earth for study. The problem? That later mission currently does not exist—and it's not clear when it will.

Last September an independent review board investigated the current state of a Mars sample return (MSR) mission and found there is a “near-zero probability”—tech speak for “no way”—of its being ready for launch by 2028. It could meet a 2030 deadline but at a cost of $10 billion, which would make it among the most expensive science projects NASA has ever undertaken.

But it's a vital part of NASA's plans.

The National Research Council's Planetary Science Decadal Survey for 2013–2022, created by a panel of dozens of leading scientists, stated that an MSR was a “highest-priority flagship mission” for that decade. A 2008 NASA preliminary planning document reported that of 55 important investigations into Mars, half would be addressed by an MSR. Looking into the idea of life on Mars, ancient or extant, is clearly a critical scientific goal for NASA with potentially immense significance for all of humanity.

The first part is already underway. A decade-old report from the Mars 2020 Science Definition Team states that using the

Perseverance rover to collect samples from the planet's surface would lower the cost of a future MSR mission. “Any version of a 2020 rover mission that does not prepare a returnable cache would seriously delay any significant progress toward sample return,” it notes. Heeding that advice, NASA designed Perseverance to collect those samples, and the rover has been doing so since 2021. Now comes the hard(er) part: delivering them to scientists on Earth.

Until very recently, the plan was to use Perseverance itself to bring the collected samples to a suitable landing spot. While this would take time away from its exploration (and, more worrisome, would make the mission run up against the expected life span of the rover), it's probably the safest and easiest method, and it's certainly the most cost-effective.

In the meantime, NASA would build a lander and a Mars Ascent Vehicle (MAV), a rocket that would take Perseverance's samples into Martian orbit. (The lander would come equipped with two sample-carrying helicopters, based on the successful Mars Ingenuity Helicopter, as a backup if Perseverance couldn't complete the task.) From there a European Space Agency Earth Return Orbiter mission would rendezvous with the MAV, ingest the sample container—literally opening up and “swallowing” it—and bring it to Earth, where it would land in the Utah desert like the OSIRIS-REx return capsule did recently with its asteroid samples.

The 2023 independent review board put the kibosh on that, however, finding that this mission cannot be accomplished in the needed time frame with the available budget. In essence, NASA has to start planning the MSR all over again. The good news is that this work has already begun, and the space agency hopes to have a new mission concept by this spring.

It's easy to point fingers at NASA for the cost overruns and schedule delays, but to be fair, the agency played by all the administrative rules. That's not to downplay mismanagement issues, which the independent review pointed out in detail, but, honestly, those kinds of problems can be expected for huge projects spanning multiple divisions of a government agency. Committees met, ideas were debated, reviewers reviewed, and the best plans advanced. Then reality intruded. Getting to Mars is *hard*. Many missions never make it. Adding the incredibly complex technical issue of not only getting back but doing so after a complicated orbital rendezvous makes matters more than twice as hard. Just getting into orbit from the Martian surface is ridiculously difficult, and NASA's important requirements for testing and redundancy—in the case of the MAV, at least—make it all but impossible under the current plan.

Where does this leave things? Well, the MSR could be canceled, but that is clearly the worst possible option. Given the mission's scientific importance—and all the time and money already invested, as well as the efforts undertaken by Perseverance—this idea shouldn't be considered seriously. NASA could trim the MSR's budget, but at this point under the current plan, that would do more harm than good. There's no science being done with an MSR, so all the engineering is geared toward picking up the samples and getting them to Earth. Cutting any of the tech needed for that could jeopardize the mission.

So here's my radical thought: Fund it. *Fully*. Give NASA what it needs to make this mission work, including a wide-enough margin for technical safety considering the difficult nature of the engineering and management required.

By “fund it,” I don't mean take needed money away from other deserving endeavors, as has happened when other NASA missions have run over budget. And I don't think it should become a separate line item in NASA's budget, as the James Webb Space Telescope did when its costs bloated. That approach might suffice for this particular case, but it is not a long-term solution for NASA's predicament.

The basic issue here is that NASA's funding is a zero-sum game, so cost overruns in one mission affect other projects. But the money shuffling wouldn't be so dire if NASA simply had a bigger overall budget. This increase would also fix many of the management problems pointed out in the 2023 MSR report, allowing NASA to hire more technical and administrative staff.

This funding shouldn't be controversial, but NASA's finances are hugely exaggerated in public perception compared with the actual budget. According to one poll, in 2018 the average American thought NASA received more than 6 percent of federal spending, when in reality it gets only 0.5 percent. Given the amazing things NASA achieves with this tiny slice, a dedicated effort to correct this misconception would make increasing the space agency's funding much less of a political struggle.

From a strictly economic point of view, NASA returns far more money than it is given. The agency estimated that it generated an economic output of $71.2 billion in 2021; that puts its return on investment at around $3 for every $1 going in. And, of course, we get a lot more from NASA than simply economic benefits.

In general, NASA's science and exploration enjoy broad bipartisan support. This fact is especially remarkable in today's political environment, where it might be hard to get the two parties to agree on the time of day and where Republicans have a history of trenchant antiscience stances—especially when it comes to climate science, a field NASA heavily supports.

Increasing NASA's resources should be a no-brainer. Instead Congress has tended to target NASA whenever a budgetary ax is wielded. This makes zero sense given how small a portion the agency gets. Cutting NASA's funding is like making room on your computer's hard drive by deleting tiny text files while ignoring the gigabytes of movies you've already watched.

Please note that I'm talking about what we *ought* to do. That may be a stretch with a Republican-led U.S. House of Representatives that in 2023 proposed bludgeoning NASA with a 22 percent cut that would kill the MSR, end moon landings and lead to 4,000 layoffs. Perhaps if the public were more vocal, Congress might listen. *Might*.

A monkey wrench in all these works is the bipartisan Fiscal Responsibility Act of 2023, intended to thwart debt default by the federal government. Part of the fallout from this act, which became law last June, is a cap on NASA's budget until 2025. This cap has had an impact already: NASA officials are considering cuts to the Hubble Space Telescope and the Chandra X-ray Observatory, two of the space agency's workhorses. Increasing the budget for an MSR is essentially impossible as long as this act is in effect, and the uncertainty about funding makes it difficult for NASA to know exactly how to move forward on any new designs.

If the MSR—and NASA itself—can weather these setbacks for the next two or three years, there may yet be a path forward. Despite all this havoc, the argument for increasing NASA's overall budget still stands. Boosting it by, say, 20 percent to $30 billion a year would ease a vast amount of pressure the agency finds itself under when proposing and building new missions. Even doubling its funding would hardly make a dent in national spending, and the payoff would be tremendous. This isn't to say that everything NASA does is cost-effective; for instance, I have been vocal about the enormously bloated and decreasingly useful Space Launch System rocket. But that project's delays and overruns can be traced to congressional meddling. With less pork-barrel legislation and better management, NASA could deliver on its promise of bringing the universe to Earth.

With an MSR, we have a real shot at investigating some of humanity's oldest and most fundamental philosophical questions.

How did we get here? Are we alone? The cost to find these answers, even in the near term, is relatively trifling.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

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

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Statistics

- **Scientists Destroy Illusion That Coin Toss Flips Are 50–50**
  Researchers go to great lengths to prove a tiny bias in coin flipping

Scientists Destroy Illusion That Coin Toss Flips Are 50–50

Researchers go to great lengths to prove a tiny bias in coin flipping

By Shi En Kim

Thomas Fuchs

The phrase “coin toss” is a classic synonym for randomness. But since at least the 18th century, mathematicians have suspected that even fair coins tend to land on one side slightly more often than the other. Proving this tiny bias, however, would require hundreds of thousands of meticulously recorded coin flips, making laboratory tests a logistical nightmare.

František Bartoš, currently a Ph.D. candidate studying the research methods of psychology at the University of Amsterdam, became intrigued by this challenge four years ago. He couldn't round up enough volunteers to investigate it at first. “Nobody was stupid enough to spend a couple of weekends flipping coins,” he says. But after he began his Ph.D. studies, he tried again, recruiting 47 volunteers (many of them friends and fellow students) from six countries. Multiple weekends of coin flipping later, including one 12-hour marathon session, the team had performed 350,757 tosses, shattering the previous record of 40,000.

The flipped coins, according to findings in a preprint study posted on arXiv.org, landed with the same side facing upward as before the toss 50.8 percent of the time. The large number of throws allows statisticians to conclude that the nearly 1 percent bias isn't a fluke. “We can be quite sure there is a bias in coin flips after this data set,” Bartoš says.

The leading theory explaining the subtle advantage comes from a 2007 physics study by Stanford University statistician Persi Diaconis and his colleagues, whose calculations predicted a same-side bias of 51 percent. From the moment a coin is launched into the air, its entire trajectory—including whether it lands on heads or tails—can be calculated by the laws of mechanics. The researchers determined that airborne coins don't turn around their symmetrical axis; instead they tend to wobble off-center, which causes them to spend a little more time aloft with their initial “up” side on top.

For day-to-day decisions, coin tosses are as good as random because a 1 percent bias isn't perceptible with just a few coin flips, says statistician Amelia McNamara of the University of St. Thomas in Minnesota, who wasn't involved in the new research. Still, the study's conclusions should dispel any lingering doubt regarding the coin flip's slender bias. “This is great empirical evidence backing that up,” she says.

It isn't difficult to prevent this bias from influencing your coin-toss matches; simply concealing the coin's starting position before flipping it should do the trick. Alternatively, you can do away with flipping altogether by jiggling a coin between your curved palms. But if your friends are unaware of the tiny bias, you may as well benefit from your slight advantage. After all, 51 percent odds beat a casino's house advantage for six-deck blackjack. “If you asked me to bet on a coin,” Bartoš says, “why wouldn't I give myself a 1 percent bias?”

Shi En Kim is a science writer based in Washington, D.C. Her work has appeared in *Chemical & Engineering News*, *National Geographic*, *Hakai Magazine*, *Slate*, *Science News*, and more. Follow her on Twitter @goes_by_kim

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Weather

- **To Predict Snowfall, NASA Planes Fly into the Storm**
  Cloud-diving expeditions reveal the hidden physics of brewing snowstorms

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To Predict Snowfall, NASA Planes Fly into the Storm

Cloud-diving expeditions reveal the hidden physics of brewing snowstorms

By Susan Cosier

Jelle Wagenaar

The aircraft's windshield was a sheet of pure gray, with visibility nearly zero as the NASA P-3 rattled through a snowstorm at 15,000 feet. Probes affixed to the wings measured ice particle sizes in the clouds, infrared thermometers recorded temperatures, and cameras snapped thousands of pictures of ice crystals. As the data rolled in, more than a dozen scientists in the cabin logged the information. Eight miles overhead, a pilot flew another plane through the very top of the same cloud. The air was so thin that he wore a spacesuit.

This eight-hour mission was one of many conducted over three years for a NASA program called Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS). The project involves more than 300 atmospheric scientists, meteorologists and crew members. Data from their flights, which were completed in February 2023, are filling gaps in scientists' knowledge of snowstorm physics—such as where in a cloud ice crystals form and the conditions under which they fall out as snow. The findings will be used to help forecasters better predict where snow will fall and how much will accumulate—a difficult task, much to the chagrin of meteorologists, skiers and schoolchildren hoping for snow days.

“We're really trying to understand how all these different processes act together to produce the snowstorms that create the havoc,” says Robert M. Rauber, a recently retired atmospheric scientist at the University of Illinois Urbana-Champaign who serves as one of the project's principal investigators.

When cold air from the poles meets warm, moist air from the tropics, it creates ice crystals that may eventually become heavy enough to fall as snowflakes. But predicting where snowstorms will hit and how much snow they will leave behind is a notoriously challenging task. That's because the journey from ice crystal to snow squall is so complicated and meandering.

The crystals often form near the top of a cloud, then drift slowly downward. If there are any nearby updrafts in the cloud, though, the crystals may get swept back skyward—where they can combine with other ice crystals to become faster-falling snowflakes. These flakes then organize into bands, which are commonly depicted in weather forecasts as colored strips showing where the heaviest snows will likely occur. But the factors that govern how these bands form are still largely unknown. And any snow reaching the ground may still melt, depending on the warmth of the earth.

Clouds typically consist of many horizontal, cakelike layers, each with different properties. Snowstorm forecasters in the 1970s and 1980s watched for patterns and used models that drew information from just a few of those layers; today better instruments and computer modeling have allowed meteorologists to examine eight times as many. But in making predictions, more data are always better, and forecasters have to work mostly with observations from past research projects to interpret satellite observations and inform their models.

“Our forecasts have improved pretty steadily over the past few decades, but we need a lot more information on the gory details of what happens in those storms,” says Jim Steenburgh, an atmospheric scientist at the University of Utah, who was not involved in the IMPACTS project.

In 2009 Rauber's team began looking more closely at the insides of snowstorms through a project called Profiling of Winter Storms (PLOWS). Using advanced radar technology on the ground and in planes, the scientists collected amazingly detailed data on the microphysical properties of Midwest snowstorms. It showed what Rauber calls snow plumes: areas within a cloud where convection-driven wind blows upward, even as ice crystals fall down. “That's when we said, ‘Holy smokes, there's a lot of stuff going on here,’” he says. These next-generation airborne radar systems “changed our whole view of these storms.”

A decade later Rauber and collaborators began making IMPACTS flights to study U.S. Atlantic coast snowstorms, which are fueled by humid ocean air. The team used even more advanced radar and lidar equipment to help reveal the presence and ratio of supercooled water and ice crystals in a cloud, using a measure called reflectivity. This allowed them to study how that ratio changes depending on variables such as temperature. Short- and medium-wavelength radar also gave views of minuscule particles, as well as the overall structure of the cloud, at high resolutions. And by flying two planes simultaneously—the first project of its kind to do so—the researchers followed how the ice crystals formed within and at the top of a storm system.

These data from the project's 35 flights revealed the microphysical processes by which snowflakes become heavy enough to fall: aggregation and riming. In aggregation, ice crystals combine and grow into snowflakes; in riming, ice crystals pick up supercooled water droplets as they fall. The IMPACTS project provided some of the most extensive observations of snowflakes created by riming in a cloud.

“We're trying to use the radar-reflectivity information to figure out if one or both of those processes are present in regions where it's snowing heavily. Is it aggregation? Is it riming? What's going on in there?” says IMPACTS lead investigator Lynn McMurdie, who works as an atmospheric scientist at the University of Washington.

With a better idea of how ice crystals become heavy enough to fall from a cloud, scientists are now using IMPACTS data to better understand what happens in the snow bands in which the crystals fall—specifically, how the bands that result in the heaviest snowfalls form. Future analyses could focus on how the structure of snow clouds changes with time and affects storm strength. Although the recent measurements focused on the U.S. Atlantic coast, the factors that contribute to devastating snowstorms could likely be applied elsewhere.

In future projects, slower-flying vehicles such as drones could capture more detailed information from various cloud layers simultaneously, revealing more about how ice crystals form and change. But for now simply identifying which physical processes are at play in a looming storm can help forecasters make better predictions, according to Brian Colle, a Stony Brook University atmospheric scientist who worked on IMPACTS. “Just being able to say that this region is going to get enhanced snowfall because of snow-band activity is a step forward from where we've been in the past.”

Susan Cosier is a freelance journalist focused on science and the environment. She is based in Chicago. Follow Cosier on Twitter @susancosier

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