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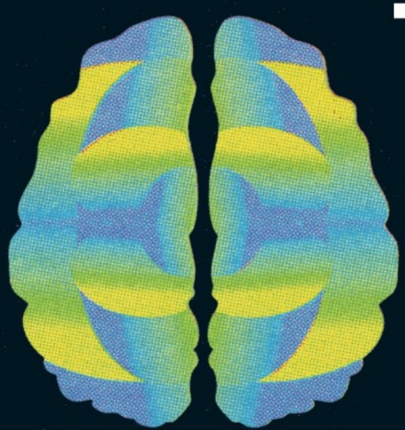
Mirror Cells Could Destroy Life on Earth

The Art World's Battle with Mold

The Search for the First Stars



The Hardest Problem in Science

Will brain science deliver answers about consciousness or hit another wall?

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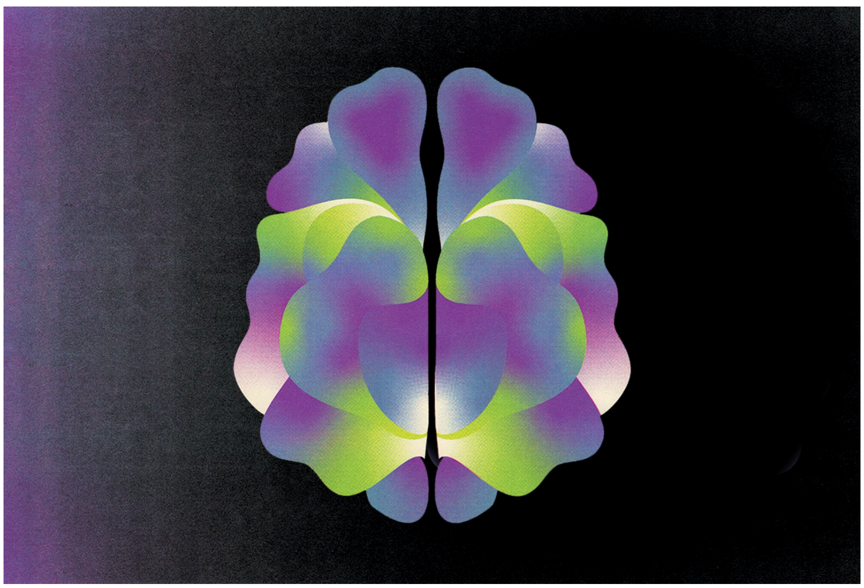
Why consciousness is the hardest problem in science

Will brain science deliver answers about consciousness or hit another wall?

By Allison Parshall edited by Seth Fletcher



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Until half a billion years ago, life on Earth was slow. The seas were home to single-celled microbes and largely stationary soft-bodied creatures. But at the dawn of the Cambrian era, some 540 million years ago, everything exploded. Bodies diversified in all directions, and many organisms developed appendages that let them move quickly around their environment. These ecosystems became competitive places full of predators and prey. And our branch of the tree of life evolved an incredible structure to navigate it all: the brain.

We don't know whether this was the moment when consciousness first arose on Earth. But it might have been when living creatures began to really need something like it to combine a barrage of sensory information into one unified experience that could guide their actions. It's because of this ability to *experience* that, eventually, we began to feel pain and pleasure. Eventually, we became guided not just by base needs but by curiosity, emotions and introspection. Over time we became aware of ourselves.

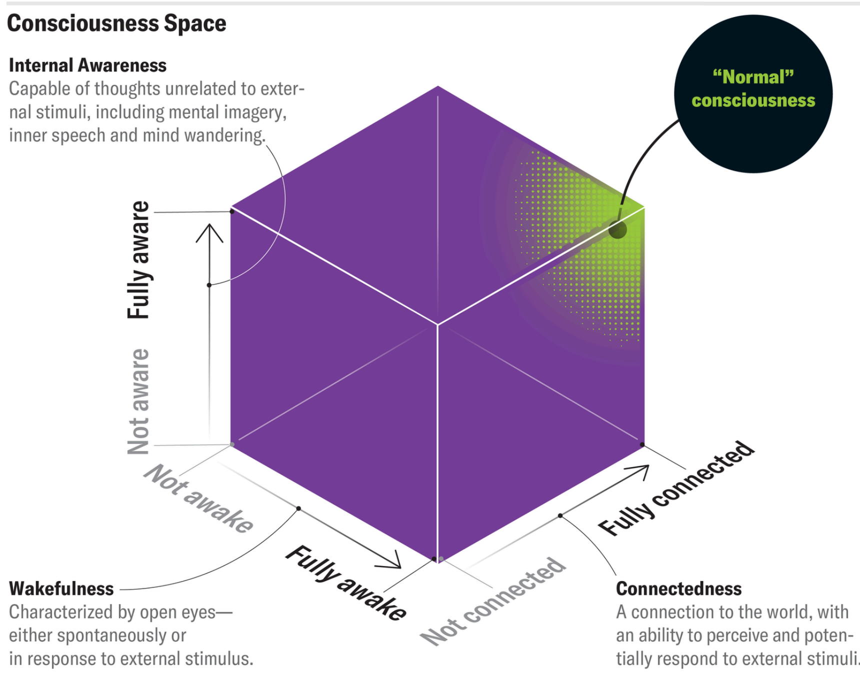
This last step is what we have to thank for most of art, science and philosophy—and the millennia-long quest to understand consciousness itself. This state of awareness of ourselves and our environment comes with many mysteries. Why does being awake and alive, being *yourself*, feel like anything at all, and where does this singular sense of awareness come from in the brain? These questions may have objective answers, but because they are about private, subjective experiences that can't be directly measured, they exist at the very boundaries of what the scientific method can reveal.

Still, in the past 30 years neuroscientists scouring the brain for the so-called neural correlates of consciousness have learned a lot. Their search has revealed constellations of brain networks whose connections help to explain what happens when we lose consciousness. We now have troves of data and working theories, some with mind-bending implications. We have tools to help us detect consciousness in people with brain injuries. But we still don't have easy answers—researchers can't even agree on what consciousness is, let alone how best to reveal its secrets. The past few years have seen accusations of pseudoscience, results that challenge leading theories, and the uneasy feeling of a field at a crossroads.

Yet the stakes for understanding consciousness have never been higher. We've built talking machines able to imitate consciousness so well that we can't always tell the difference. Sometimes these artificial-intelligence models claim outright to be sentient. Faced with an existential unknown, the public is turning to the field of consciousness science for answers. "The tension, you know, it's palpable," says Marcello Massimini, a neurophysiologist at the University of Milan. "We're going to be looking back at this period."

Consciousness is all you really know. It's the voice you hear in your head, your emotions, your awareness of the world and your body all rolled into one unified experience. "Everything comes down to it, everything," says cognitive neuroscientist Athena Demertzi of the University of Liège in Belgium. "It's the translation of the world that we have." Philosophers and scientists alike struggle to define consciousness without appealing back to what it *feels* like to experience—what philosophers call "definition by pointing." But they're pointing to a real phenomenon. It's your consciousness that goes wonky when you take hallucinogens, even as your body and environment stay the same. When you go under general anesthesia, it appears to go out like a light. When you dream, some strange form of consciousness persists, even if it's disconnected from the outside world.

Some scientists have used these different states of consciousness to chop up conscious experience into at least three pieces: wakefulness, internal awareness and connectedness. In a "normal" state of consciousness, you have all three. You're awake with your eyes open, a state that is sustained by signals from your brain stem. You're internally aware, forming thoughts and mental imagery. And you're connected to the outside world, with your brain receiving and processing information from the five senses.



Jen Christiansen; Source: "Near-Death Experience as a Probe to Explore (Disconnected) Consciousness," by Charlotte Martial et al., in *Trends in Cognitive Sciences*, Vol. 24; March 2020 (*primary framework reference*)

How the brain gives rise to these strange experiences is a question that has haunted neuroscience for as long as the field has existed. Massimini was driven wild by the mystery in medical school, when he held a brain in his hands for the first time. "This is an object with boundaries, with a given weight, a little bit like tofu. It's not particularly elegant," he says, but "inside this object that you can hold in your hand, there is a universe." Many philosophical traditions have dealt with this apparent disconnect by saying the mind—or the soul—is not made of the same physical stuff as our bodies, a position called dualism. Science has instead flourished by assuming the opposite and siding with a theory called materialism, which presumes that everything we observe somehow arises from physical matter, including consciousness.

Perhaps knowing they weren't up to the job of explaining how this happens, neuroscientists shied away from the enigmas of consciousness until the 1990s. "You had to be retired or religious or a philosopher to be able to talk about it," says neuroscientist Christof Koch, a member of the *Scientific American* board of advisers and chief scientist at the Tiny Blue Dot Foundation, a research nonprofit focusing on perception science. In 1990 Koch and Nobel laureate Francis Crick, the co-discoverer of DNA, directly challenged this taboo. They published a paper that laid out an ambitious plan to study the neurobiology of consciousness and launched the field as we know it today.

Their plan came at a good time. That same year neuroscientists invented a new way to observe the working brain called functional magnetic resonance imaging (fMRI). Using brain scanners, they track changes in blood flow to reveal which brain regions are active at a given time, producing colorful images of the brain in action. Koch, who studied vision, thought that by measuring people's brain responses as they looked at special optical illusions, scientists could figure out which parts of the brain are activated when something is consciously perceived. Some of the illusions used can be perceived in one of two ways; one example is Rubin's vase, which can be seen either as a vase or as two faces in profile. The image never changes, so the brain is always receiving the same information, but people's conscious experience of it can easily switch back and forth. Another visual test, called binocular rivalry, has a similar effect: each eye is shown a different image, and people perceive either one or the other but never a mix of the two. If neuroscientists could scan people's brains as their conscious perception switched, they could find parts of the brain that were associated with that change: the neural correlates of consciousness.

Koch bet big, literally. In 1998, at a consciousness-science conference in Germany, he bet philosopher David Chalmers a case of wine that researchers would discover a "clear" pattern of brain activation underlying consciousness within 25 years. Chalmers took the bet, thinking 25 years "might be a bit optimistic," he says.

It was extremely optimistic. These early neural-correlate studies of vision, which dominated the field in the 1990s, suggested places that may be less correlated with visual awareness: the regions where input from our eyes first enters the brain. These low-level sensory-processing areas contain a lot of information that our conscious selves aren't privy to. These areas appear to continue receiving sensory information when we're under anesthesia as well. As that information travels "up" the wrinkly outer layer of the brain, called the cortex, it enters areas that pick out and process higher-level details—such as the faces in an image—and conscious awareness builds.

So consciousness seems to happen in some region outside these early visual-processing areas—but there is no consensus on where.

Today there are dozens of competing theories of how the brain generates consciousness. They have different starting points, different goals and even different definitions of consciousness. The most popular is global neuronal workspace theory (GNWT), which envisions consciousness as a kind of stage. When something enters your conscious awareness—an itch, say, or the buzz of your refrigerator—it's thrust onto the stage and spotlighted in a process called ignition. Things on the stage, or in the "global workspace," get broadcast to the rest of the brain, where they're able to guide action, direct attention, and more.

Higher-order theories conceive of consciousness as a high-level representation of what is going on in other parts of the brain. For you to be conscious of a refrigerator's buzzing, your brain cannot just represent the buzz by activating its auditory parts (which are located near the temples). The buzz must also have a corresponding "meta-representation" in the frontal parts of the brain that are responsible for higher-order thinking—such as the thought "I am hearing the refrigerator buzzing."

Reentry and predictive processing theories (PPTs), on the other hand, propose that consciousness emerges from our brain's balancing of two processes: perception and prediction. If you have ever seen something that wasn't there simply because you expected to see it, you know how much our brain's predictions can govern what we actually perceive. Neuroscientist Anil Seth of the University of Sussex in England, who favors PPTs, describes conscious perception as a “controlled hallucination,” with the brain’s best guess of what’s going on around you mapping onto what you consciously perceive.

> There's a chasm between our everyday experiences and what science can explain.

Then there’s integrated information theory (IIT), a mathematical and philosophical theory that stands out from the rest because it doesn’t start with the brain. Instead it starts with consciousness itself and the observations we can make about its properties, then asks what kind of system could allow something with these properties to exist. IIT takes consciousness to be differentiated—there are a lot of things you could be experiencing right now but aren’t, making your consciousness rich in information. And it is also unified, or integrated—all your diverse experiences are bundled into one single stream of consciousness. Mathematically, these two features together make the system very complex. And from this complexity comes consciousness.

Most eye-catching of all, IIT implies that consciousness could be present outside of living systems, a kind of panpsychism. This idea, plus the theory’s relative lack of grounding in the brain and coverage in the media, would make IIT a flashpan of controversy. But first it would inspire one of the most important insights we have into how consciousness works.

In the early 2000s, while studying in the U.S., Massimini began performing experiments with a device for probing the brain that did two things at once: deliver painless magnetic pulses to the brain and detect brain waves, both from outside the scalp, techniques called transcranial magnetic stimulation (TMS) and electroencephalography (EEG), respectively. Once back in Italy, he managed to secure a grant to buy a TMS-EEG machine for his university despite a “desperate” research-funding situation in the country.

A few years later he and a colleague “did something crazy,” he says. They loaded the machine into a truck and drove more than nine hours to Liège. “We didn’t say anything to anybody. This is a machine belonging to the university after all.” But the opportunity was too good to pass up. A neurologist in Liège named Steven Laureys had founded the Coma Science Group for treating and learning from patients with disorders of consciousness, and Massimini believed his new device could be used to measure someone’s level of consciousness from their brain activity.

Researchers had tried to measure the difference between conscious and unconscious brains with other brain-imaging techniques before, without much success. But adding TMS let scientists stimulate the outer layers of the cortex, causing neurons in a specific area to fire. Then EEG measured brain waves to reveal how that stimulation spread. “It’s like knocking on the brain directly,” Massimini says, “to probe the internal structure.”

You can also think of TMS like dropping a rock in a pond. In a conscious brain (whether awake or dreaming), the disturbance ripples outward as neurons cause neighbors in their networks to fire. But unlike waves in water, each of those ripples of neuron activity begets more ripples, spreading in a complex and far-reaching way throughout the brain’s networks. In dreamless sleep, this doesn’t happen, Massimini had previously found. TMS stimulates the brain, and the neurons fire, but the wave of activity isn’t picked up by neighboring neurons. If there are ripples, they don’t spread far. The complexity seen during wakefulness is gone.

In Liège, Massimini and his colleagues tested the technique on people with various disorders of consciousness—patients who were in vegetative states, or were in minimally conscious states, or were outwardly unresponsive but internally aware. They found that people whose brains exhibited a more complex response were more likely to be conscious. This relation could be represented as a single number, called the perturbational complexity index, or PCI.

PCI is a very crude measure of consciousness, but it can estimate someone's place on the spectrum of consciousness quite reliably. And it suggests that complexity is an important part of a conscious brain. In an awake or dreaming brain, diverse networks of neurons are in constant back-and-forth communication with one another. In this way, conscious brain activity is both differentiated (or rich in information) and integrated (forming one unified whole)—principles that Massimini borrowed from IIT, the theory that doesn't begin with the brain. These interactions build up complexity, or what IIT theorists call a "cause-effect structure," so that when you stimulate one part of a conscious brain, other parts respond.

But during dreamless sleep or when someone is under anesthesia, all that communication goes away. "Everything collapses," Massimini says. "The cathedral falls apart." Slow brain waves travel across the cortex as neurons cycle rhythmically between two electric states. In the "silent periods" between the waves, neurons enter what's called a down state, in which they can't respond to electric signals from their neighbors. This state is why there's silence when you stimulate an unconscious brain with TMS: "No feedback, no unity, no complexity," he says.

Of course, this loss of complexity during sleep and anesthesia is transient; disorders of consciousness can be permanent. "Why can I reverse sleep in a few seconds, and I can reverse anesthesia in the course of minutes, but I might not ever be able to reverse this pathological state?" asks George Mashour, an anesthesiologist and neuroscientist studying consciousness at the University of Michigan Medical School. Massimini hopes that we can eventually learn how to jump-start consciousness—rebuild the cathedral—for people who are in vegetative or minimally conscious states.

> “It feels like there’s been a hard-won legitimacy to the study of consciousness over the past 30 years.” —Anil Seth, *University of Sussex*

Yet understanding brain-network complexity does not solve the mystery of consciousness. These findings can help explain how a brain can reach the state of consciousness but not what happens once it’s gotten there, Mashour points out. Changes in someone’s PCI value can’t explain, for example, why The Dress looks blue and black one moment and white and gold the next. It can’t explain how a toothache feels different from a headache, how someone without functioning circulation can have a near-death experience, or how the psychedelic drug 5-MeO-DMT makes time seem to stop and obliterates your sense of self.

There’s a chasm between our everyday experiences and what science can explain. “No one really has a theory that closes the explanatory gap,” says Tim Bayne, a philosopher at Monash University in Melbourne. “But that’s a problem on us, not the brain.”

At a June 2023 conference in New York City, Koch gave Chalmers his case of wine and conceded that he had lost their bet. “It’s clear that things are not clear,” Chalmers said.

That weekend the evidence looked particularly murky. The results of a massive research project pitting IIT against GNWT had recently been shared. The project, led by a group called the Cogitate Consortium, involved three different measuring techniques used in eight different institutions around the world. Researchers developed predictions from each theory about what should happen in the brain when an image is consciously perceived versus when it’s not. Testing those predictions could challenge or even falsify either theory.

Both theories came away bruised. IIT holds that consciousness arises mostly from sustained activity in the back of the brain. This “hot zone” sits at the intersection of many sensory networks of neurons. GNWT, in contrast, predicts that a stimulus (such as an image) rises to the level of consciousness only when there is an “ignition” to the workspace in frontal parts of the brain such as the prefrontal cortex, which is known for planning and decision-making. GNWT also predicts that this ignition signal will appear as two discrete spikes of activity—one when an image is first presented and one when it’s removed—whereas IIT predicts sustained activity as long as a person is looking at an image.

The results were extremely mixed. Although there was sustained activity in the back of the brain associated with conscious perception, networks in the region weren’t synchronized in the way that IIT predicts. And although there was a signal in the prefrontal cortex when images were first presented, there was not a second signal when they were removed, contrary to GNWT’s predictions.

Then, a few months later, the field erupted. An open letter calling IIT pseudoscience was published online in September 2023, signed by 124 researchers in or adjacent to the field. The argument focused less on the theory than on its coverage in the media, which the letter’s authors saw as credulous. The authors also took issue with the panpsychist implications of IIT, highlighting descriptions of it as unscientific and “magicalist.” “These bold claims threaten to delegitimize the scientific study of consciousness,” many of the authors wrote in a follow-up article.

The prospect that the field could lose its legitimacy hung over the fight. One side feared IIT’s reputation would drag consciousness science even further toward the fringes, and the other worried that publicly tarring one theory with a “pseudoscience” label would lead to the downfall of the entire field. “My greatest fear is that we get another ‘consciousness winter’ wherein just talking about consciousness is considered pseudoscientific bunk,” wrote Erik

Hoel, a consciousness researcher at Tufts University who has published extensively on IIT's limitations, in a post defending the theory.

The debate, which took place largely in online posts and in the media, was finally hashed out in the pages of *Nature Neuroscience* last March. Since then, the scientists involved have seemed to be trying to put the ugly chapter behind them. But now there is a sense that the field has arrived at an "uneasy stasis," Seth and his colleagues wrote recently in the journal *Frontiers in Science*.

"It feels like there's been a hard-won legitimacy to the study of consciousness over the past 30 years," Seth says. And there are important results to show for it. We now know that large parts of the brain—for example, the cerebellum, a structure near the brain stem that contains a majority of the brain's neurons—is apparently not involved in consciousness. We've learned about specific brain regions that are associated with specific pieces of conscious experience, such as our sense of self. We're also getting hints that ancient structures deep in our brain, such as the thalamus, may be more involved than neuroscientists had previously thought.

> Comparing consciousness among species could reveal why it exists in the first place.

But underneath it all lurk countless unknowns. "There's still disagreement about how to define [consciousness], whether it exists or not, whether a science of consciousness is really possible or not, whether we'll be able to say anything about consciousness in unusual situations like [artificial intelligence]," Seth says. It stands in contrast, perhaps unfairly, to other scientific journeys of discovery, such as the mapping of our genetic code in the Human Genome Project or of the cosmos with the help of the James Webb Space Telescope, he adds.

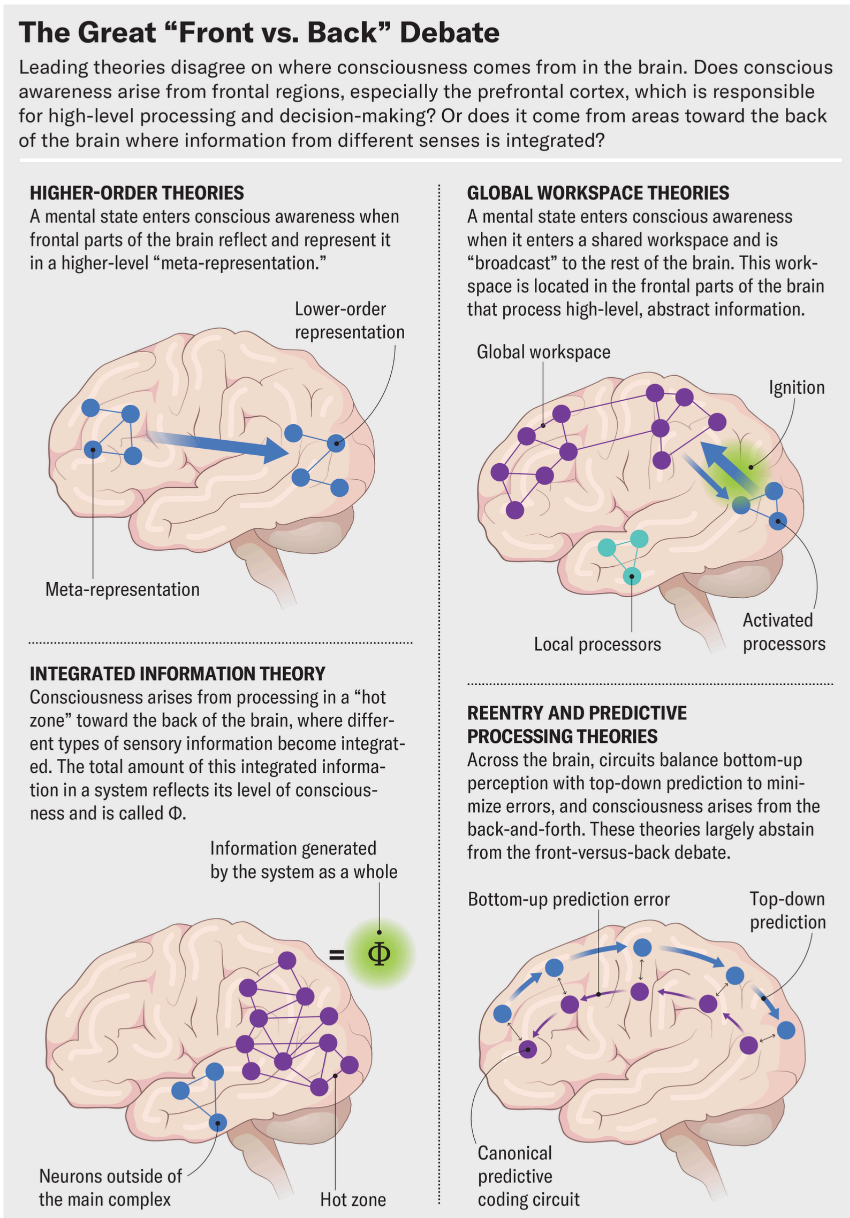
“It’s a wonderful moment but also kind of sobering,” Bayne says. Building bigger and bigger particle colliders is a pretty good tactic for revealing the stuff of the subatomic world. But for revealing the stuff of consciousness, there’s no sure bet. “If Bill Gates gave me $100 billion tomorrow and said, ‘Okay, find out about consciousness,’” he says, “I wouldn’t know what to do with that money.”

Artificial intelligence may soon force our hand. In 2022, when a Google engineer publicly claimed the AI model called LaMDA he had been developing appeared to be conscious, Google countered that there was “no evidence that LaMDA was sentient (and lots of evidence against it).” This struck Chalmers as odd: What evidence could the company have been talking about? “No one can say for sure they’ve demonstrated these systems are not conscious,” he says. “We don’t have that kind of proof.”

As these machines get better at imitating human dialogue—sometimes even claiming outright to be conscious—ethicists, AI companies and the concerned public are increasingly looking to consciousness research for answers. “Suddenly those philosophical questions have become very practical questions,” Chalmers says.

These questions are bigger and older than AI. Where does consciousness exist in the world around us, and how can we prove it? Scientists and philosophers are increasingly studying animals, human fetuses, brain organoids and AI to figure out what common principles could underlie consciousness.

Researchers have often studied consciousness by focusing exclusively on humans, because the only consciousness we can ever truly be sure exists is our own. For everyone else, we must rely on behavioral cues and trust they are not a “philosophical zombie,” with all the outward signs of consciousness but without any of the internal experience. We extend this assumption to fellow humans every day. Sometime in the 20th century, though, scientists stopped doing so for animals. “When I started my graduate studies in the 1990s, ‘chimpanzees aren’t conscious’ was the default position for a lot of philosophers,” says Kristin Andrews, a philosopher studying animal minds at the City University of New York Graduate Center.



Jen Christiansen; Source: “Theories of Consciousness,” by Anil K. Seth and Tim Bayne, in *Nature Reviews Neuroscience*, Vol. 23; July 2022 (*primary reference*)

Yet we find consciousness only where we presume to look for it. It’s a spotlight effect, Andrews explains, and since then, our spotlight has slowly widened. First, in the 1990s, consciousness scientists broadened it to do research on lab monkeys that couldn’t be done on humans. By the time a group of scientists signed the Cambridge Declaration on Consciousness, in 2012, there was more acceptance of the idea that all mammals and some birds are probably sentient.

Now the frontier rests with fish, crustaceans and insects. Studies suggest that fish can recognize themselves in a mirror, bumblebees can play and crabs can weigh decisions based on conflicting priorities. The 2024 New York Declaration on Animal Consciousness, which Andrews co-authored, states that there is at least a "realistic possibility" of consciousness in all vertebrates and some invertebrates, such as insects, certain mollusks and crustaceans. "We can't just assume that all these animals are not conscious," says Chalmers, who signed the declaration.

Comparing consciousness among species could reveal why it exists in the first place. "People have focused a lot on where consciousness is in the brain and perhaps less so on what it's *for*," Seth says. He theorizes that consciousness is intrinsically linked to life. Living beings can do only one thing at a time, and to choose what to do, they must bring a lot of relevant information together into one stream.

Even if that is right, it doesn't mean carbon-based life is the only arena where consciousness can happen. "Just as we can build things that fly without flapping their wings, maybe there are other ways of being conscious that don't require being alive," Seth says. "We should really take that possibility seriously."

The AI large language models (LLMs) that underpin chatbots such as ChatGPT and Claude can certainly imitate consciousness well, although today they are most likely the zombies that Chalmers and other philosophers once imagined. Even most AI enthusiasts will tell you that all an LLM does is predict which word comes next in a sentence; it doesn't "know" anything. But—to be strictly philosophical about it—can we really *prove* LLMs aren't conscious if we haven't yet agreed on how consciousness works?

Some researchers think theories rooted in the human brain, such as GNWT, could still provide clues. If the brain is like a biological computer—a dominant assumption of cognitive neuroscience—then maybe researchers can compare how LLMs process information and test for indicators of consciousness. GNWT, which was itself inspired by an early type of AI model, says information is consciously experienced once it's broadcast across the entire system. Does an LLM do something similar?

Not everyone buys the brain-computer circuitry analogy. Brains do a lot more than run algorithms that process information, Seth says. They have electric fields, and they interact with chemical signals. They are made of thousands of types of living cells that consume energy. "It's a massive assumption that none of these things matter," he says. "And that assumption has gone largely unexamined because of the power of the metaphor that the brain is a computer."

IIT proponents such as Massimini and Koch also think the underlying physical "stuff" of a system matters—and that mere simulations, including LLMs, can't yield consciousness. "It's like [how] simulating a storm will not get you wet," Massimini says, "or simulating a black hole will not bend space and time."

In consciousness science, everything comes back to the measurement problem. You can try to find markers of different states of consciousness—for instance, by scanning a person's brain while they are awake versus in slow-wave sleep, which is typically dreamless and therefore unconscious. This experimental setup assumes the subject is in fact not dreaming. But that assumption could be wrong: sometimes people do report dreams when woken from slow-wave sleep. Were they wrong? Do you trust them? How can you confirm that your assumptions about consciousness are correct when your only ground truth is someone else's word—which is not really a ground truth at all?

When we are faced with this seemingly intractable problem, it's tempting to reach for an escape valve: Maybe none of it is real. Maybe consciousness is so illusory because it is an illusion, a beautiful cathedral that exists only in our heads. This skeptical position was often put forward by the late philosopher Daniel Dennett, and it's a legitimate question. But it doesn't allow us to opt out of treating brain injuries, understanding drugs such as anesthetics and psychedelics, and grappling with our treatment of animals and the intelligent machines we're birthing. Consciousness is real to us, and therefore it is real in every way that counts.

All of science rests on inferences about things we cannot see. We can't see a black hole, Koch points out, but we can spend decades building up theories and creating instruments that let us infer their existence. Consciousness may be a more challenging case, but researchers don't plan to stop trying. With the right tools, "the sense of mystery about how material processes could give rise to conscious experiences would start to go away," Seth says.

"I don't know what will happen afterward—if it will still be impressive or not," University of Liège's Demertzi says. "But, you know, sometimes nature is so beautiful that even when it's analyzed, you're in awe."

Allison Parshall is associate editor for mind and brain at *Scientific American* and she writes the weekly online Science Quizzes. As a multimedia journalist, she contributes to *Scientific American*'s podcast *Science Quickly*. Parshall's work has also appeared in *Quanta Magazine* and Inverse. She 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.

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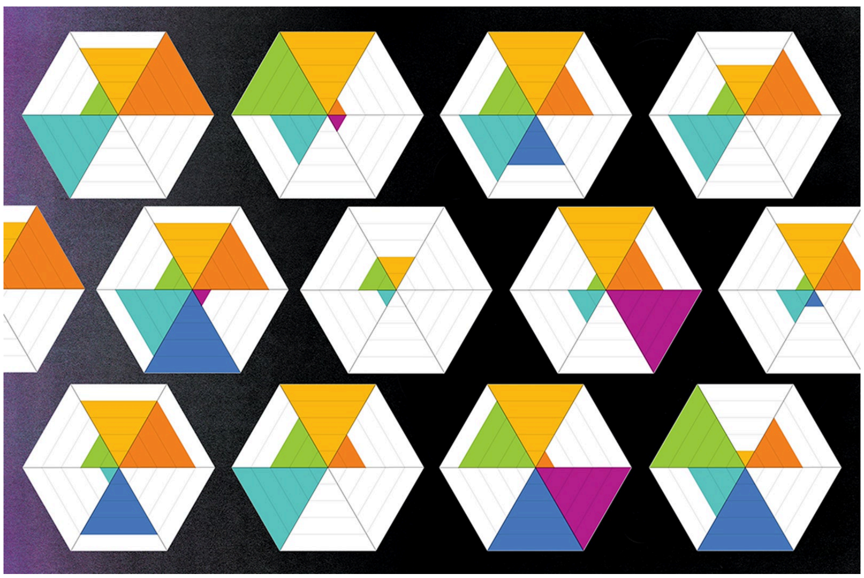
https://www.scientificamerican.com/article/what-is-consciousness-science-faces-its-hardest-problem-yet

Your guide to 29 wildly different theories of consciousness

The many, many ways researchers hope to solve the toughest mystery in science

By Allison Parshall & Jen Christiansen edited by Seth Fletcher



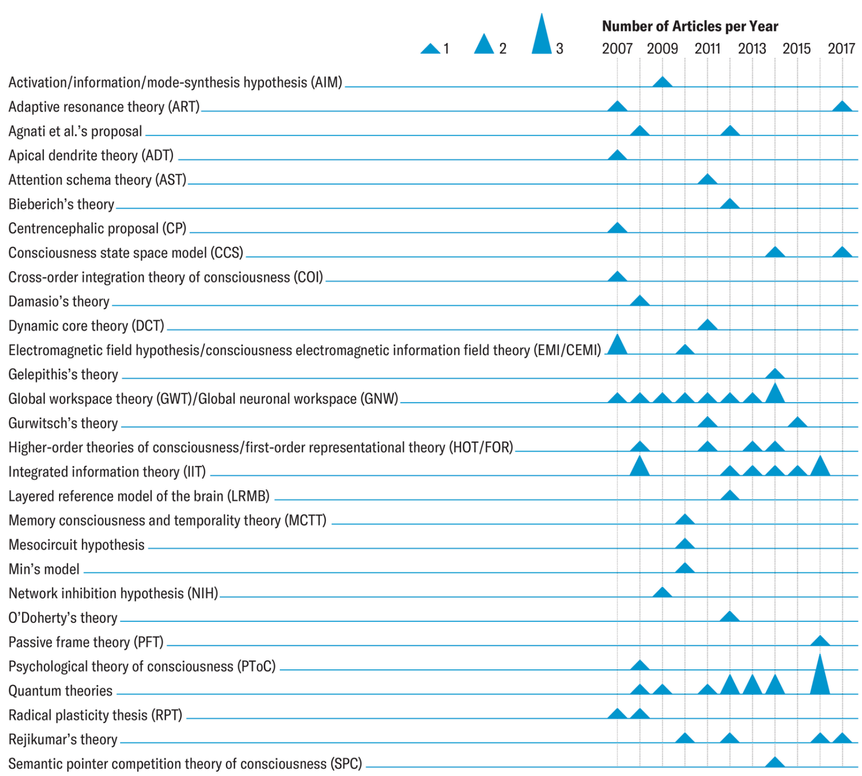
Jen Christiansen

Theorists have proposed many explanations for consciousness. They are startlingly diverse, with different goals, starting points and even definitions of consciousness. To compare them, researchers surveyed articles suggesting a theoretical model for consciousness that were published between 2007 and 2017 in English or Italian.

Some of these theories have many publications to their name, such as global workspace theories, higher-order theories and integrated information theory, three of the field’s leading models. But having more publications does not mean a theory is supported by stronger evidence—this analysis didn’t weigh the strength of study results. Instead the number of articles most likely reflects the amount of interest each type of theory garnered. This may explain why quantum theories of consciousness, which are fascinating but not yet grounded in much evidence, have been proposed so many times. Predictive processing theories, which are also influential in the field, are notably absent, perhaps because they originated as theories of perception rather than consciousness.

THEORIES INCLUDED IN THE META-ANALYSIS

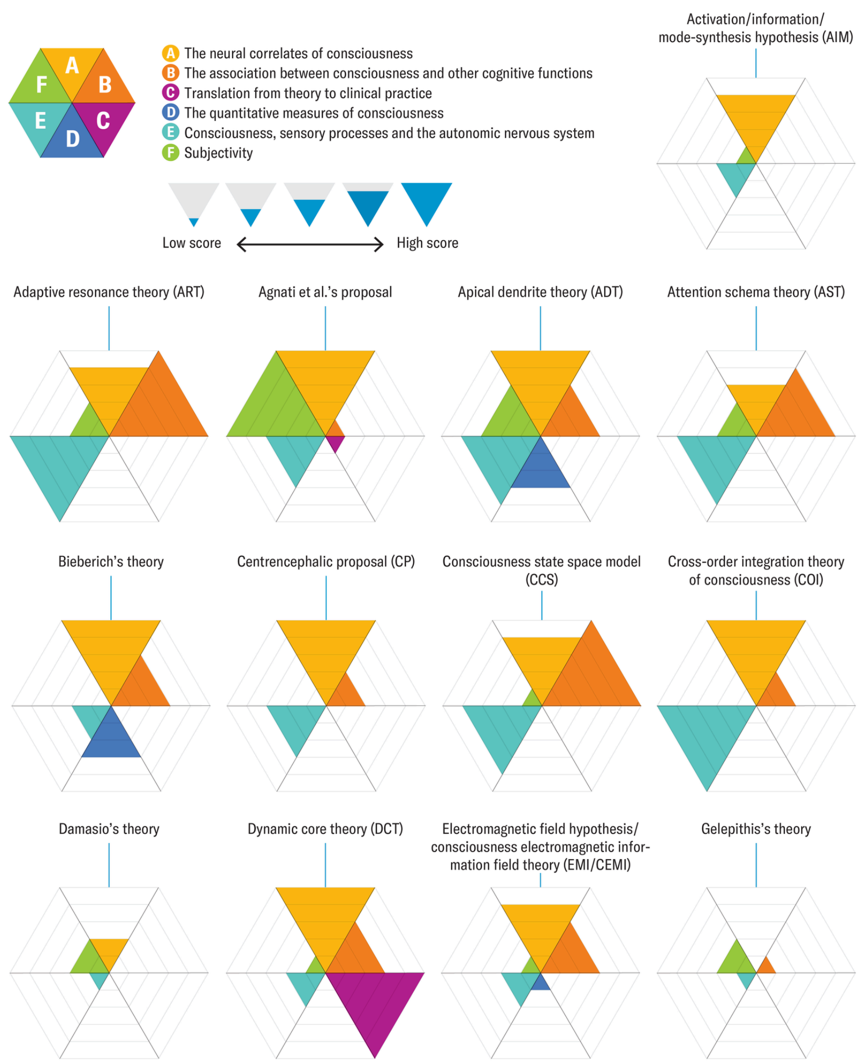
The researchers found 68 articles that analyzed theoretical aspects of consciousness and that were published between 2007 and 2017 in English or Italian. Together, they represent 29 different types of theories. More than half (18) were suggested only once, but others garnered more interest.

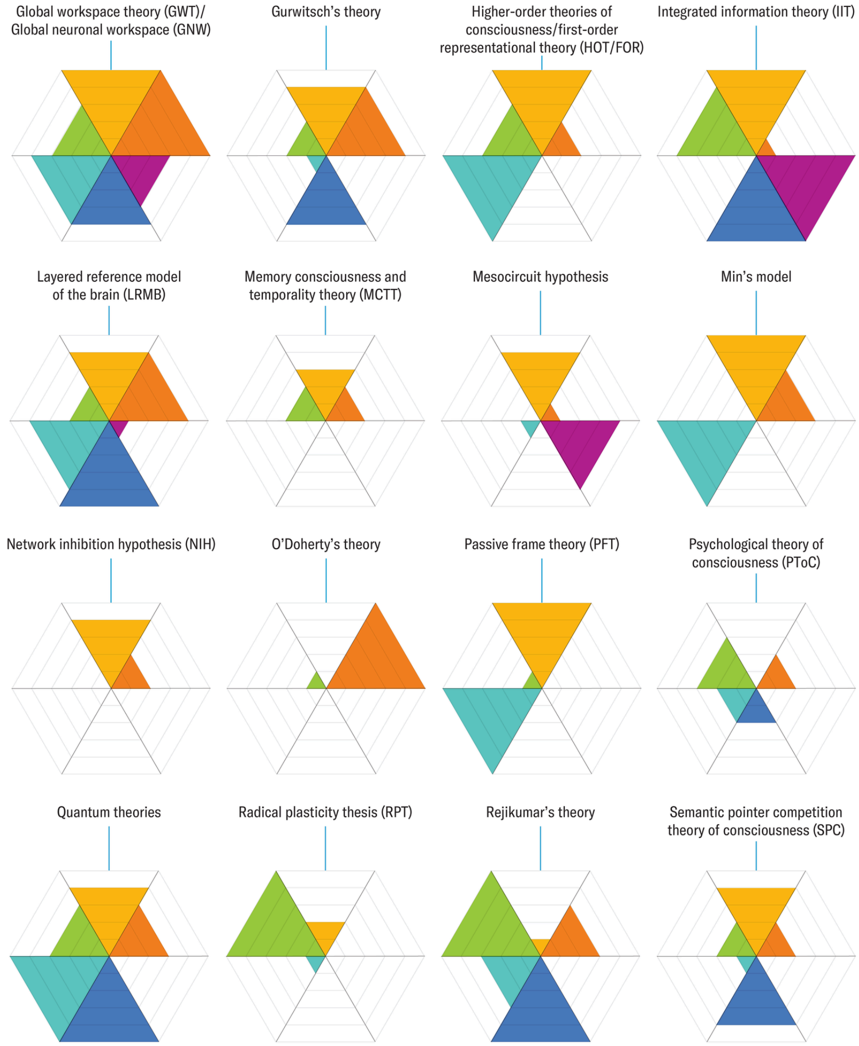


Jen Christiansen; Source: “Theoretical Models of Consciousness: A Scoping Review,” by Davide Sattin et al., in *Brain Sciences*, Vol. 11; April 2021 (*data*)

THEORY CHARACTERISTICS

All of these proposals are wildly different, and only some are supported by evidence. The researchers analyzed how each tried to address six dimensions of consciousness: (A) what brain activity correlates with conscious experience, (B) how consciousness relates to other mental faculties such as memory and attention, (C) the clinical treatment of disorders involving consciousness, (D) how levels of consciousness could be measured, (E) how consciousness relates to sensory information, and (F) where subjective experience comes from.





Jen Christiansen; Source: "Theoretical Models of Consciousness: A Scoping Review," by Davide Sattin et al., in *Brain Sciences*, Vol. 11; April 2021 (*data*)

Allison Parshall is associate editor for mind and brain at *Scientific American* and she writes the weekly online Science Quizzes. As a multimedia journalist, she contributes to *Scientific American*'s podcast *Science Quickly*. Parshall's work has also appeared in *Quanta Magazine* and Inverse. She 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.

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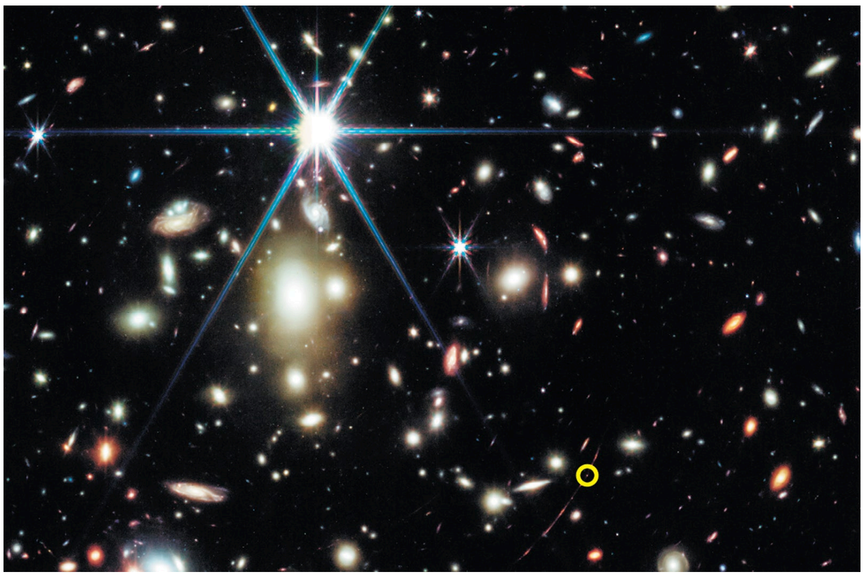
https://www.scientificamerican.com/article/your-guide-to-29-wildly-different-theories-of-consciousness

When will we see the universe’s first stars?

The James Webb Space Telescope should soon be able to spot the first generation of stars in space

By José María Diego Rodríguez edited by Clara Moskowitz



Earendel, the current record holder for most distant star ever seen, is circled in this image from NASA's James Webb Space Telescope. The star is contained within the Sunrise Arc, a magnified and distorted galaxy from the early universe.
NASA, ESA, CSA; Science: Dan Coe (STScI/AURA for ESA, JHU), Brian Welch (NASA-GSFC, UMD); Image Processing: Zoltan Levay

On Christmas Day 2021, alongside other astronomers, I watched the James Webb Space Telescope (JWST) launch from French Guiana and begin its month-long journey to its destination, 1.5 million kilometers from Earth. The trip was filled with many nerve-racking moments, particularly the week-long period in which the telescope’s tennis-court-size sun shield array slowly unfolded like origami from its bus-size liftoff configuration.

Luckily, JWST made the trip safely and began operations in the summer of 2022. Since then, the observatory has started answering some of the biggest questions in astronomy. It’s also raised many new ones.

One of the biggest surprises that has emerged is the discovery that supermassive black holes, some with masses more than a million times that of the sun, existed when the universe was no more than about 3 percent of its current age. How such massive black holes came to exist so long ago is a puzzle. Perhaps less massive black holes formed from the explosive deaths of the first stars, known as Population III stars, and those black holes later merged under the influence of gravity to form a million-solar-mass black hole.

But how could thousands of these smaller black holes have combined in the cosmically short period of hundreds of millions of years? To figure it out, we need to understand the very first stars, which, to date, no one has ever seen individually.

Known as dinosaur stars for both their primeval nature and their immense size, Population III stars existed only when the universe was very young. At that time chemistry was simple. The stars would have been made of hydrogen, helium and tiny traces of light elements such as lithium because those were the only elements that existed then.

> It’s simply amazing that humans can hope to observe such relics from the very beginning of time.

In such a pristine environment, when the universe was much denser than it is today, much more massive stars were able to form than those we can observe now. Such large stars are the analogues of 20th-century rock stars—or pop stars (pun intended). They lived fast and died young, and like all great rock bands do, they left a mark on the universe. During their short lives, just a few million years long, Population III stars churned out heavier elements such as carbon, oxygen, nitrogen, silicon, sulfur and iron through fusion within their cores. When they died in supernova explosions, those elements poured into the universe and seeded the ingredients that would later be essential to form planets and life as we know it.

What was left after one of these supernovae was, in most cases, a black hole.

Scientists have yet to observe Population III stars individually, but that could soon change. Thanks to JWST, along with a helpful boost from nature called gravitational lensing, we might get a glimpse of them as they were during their brief lifetimes or be able to detect their very bright final explosions. We might even see the shining gas around their skeletal black holes, which would appear to us as a small quasar.

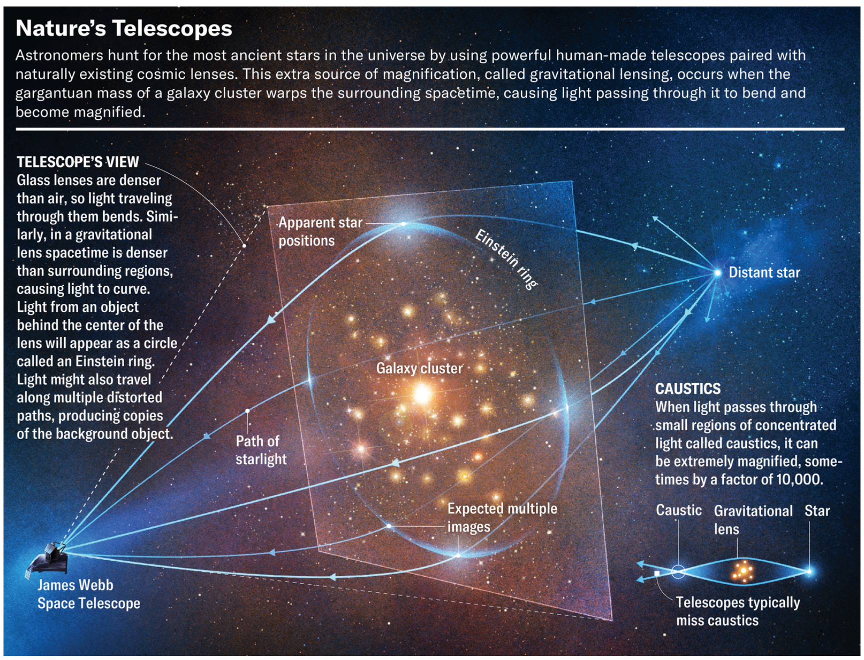
It’s simply amazing that humans can hope to observe such relics from the very beginning of time. These stars won’t just teach us about the early universe—they might also shed light on one of its biggest mysteries: dark matter. The cosmos seems to be filled with invisible matter we don’t understand, but the light of the first stars must have traveled through it on the way to our telescopes, so this light can teach us about its nature.

My personal journey to study these early stars started more than 10 years ago, after I had worked on different astronomical questions at several institutes across the U.K., the U.S. and Spain. At that point I temporarily relocated to the U.S. to work with data from the best telescope at the time, NASA’s Hubble Space Telescope, and on my favorite topic, gravitational lensing.

The primordial galaxy known as the Sunburst Act appears four times in this image from the Hubble Space Telescope. The light from the galaxy, which lies 11 billion light-years away, has been distorted and magnified into curving smudges by the mass of the galaxy cluster in the center of the image. One of the oldest known stars, Godzilla (*circled*), is visible within this galaxy.

As powerful as the Hubble and James Webb telescopes are, they are not large enough to see Population III stars without a boost. Fortunately, the universe has been kind to astronomers and has built thousands of naturally occurring telescopes that magnify the distant galaxies lying behind them. Similar to the way a piece of glass can be turned into a magnifying lens that curves light, very massive objects in the universe can bend space itself. When light travels through this warped space, it also bends. Albert Einstein predicted this molding of space and light, which is known as gravitational lensing.

The most massive objects in the universe, and thus the most powerful natural lenses, are galaxy clusters, swarms of hundreds to thousands of galaxies packed together in a relatively small volume that also contains vast amounts of the mysterious substance called dark matter. Galaxy clusters can have masses up to 1,000 times that of the Milky Way and are held together by gravity. When we point a telescope at one of them, the cluster’s gravity both amplifies and distorts our view of the background galaxies, thereby creating the gravitational lens. Light from an object behind the center of the lens will be amplified and distorted into a circular shape called an Einstein ring.



Matthew Twombly

When we point JWST toward a gravitational lens, we are adding an extra giant lens in front of the telescope, effectively transforming the observatory into a cosmic microscope. Gravitational lenses magnify only a small portion of the space behind them, just as microscopes do. And the magnification provided by the gravitational lens is not uniform: most of the area behind the galaxy cluster is magnified by factors of less than 10, but in some very small regions, termed caustics, the effect can be very strong, with magnification factors of up to around 10,000.

If a sufficiently bright but small object happens to be in one of these caustics, we can get an otherwise impossibly zoomed-in view of it. When JWST points at one of them, it acts like a telescope 100 times larger than it is, offering the opportunity to take a very high-resolution peek at the distant universe. The only catch is that the objects we can observe with this technique must be relatively small and bright. Population III stars meet these two requirements.

Astronomers are getting close to scoring front-row seats to these elusive stars. In recent years we have glimpsed some of the most ancient stars yet. In 2016, five years before the launch of JWST, astronomers used the Hubble telescope to spot Icarus, the first star observed through a cosmic microscope. Icarus lies a whopping 200 times farther away than the most distant star known before it.

Patrick Kelly of the University of Minnesota, who led the team that discovered Icarus, named it after the mythological character who flew too close to the sun, in reference to the high magnification that revealed it. The scientists first noticed Icarus because its brightness fluctuated between observations separated by months. Very few objects in the universe exhibit this type of change in brightness; after considering all plausible options, the researchers determined that a blue supergiant star was the only possible candidate that could explain the observations.

The brightness fluctuations were the result of a different lensing effect, microlensing, produced by much smaller masses. For most astrophysical objects, this effect is negligible. But for background stars whose magnification can change considerably in a matter of weeks, such as Icarus, it can lead to dimming and brightening. When a microlens temporarily aligns with a telescope, a galaxy cluster lens and a distant background star, the star’s brightness can increase by up to a factor of 10. The alignment tends to last for a few weeks. During microlensing episodes, the background star twinkles in a well-known and predictable way that allows us to recognize it as an individual star.

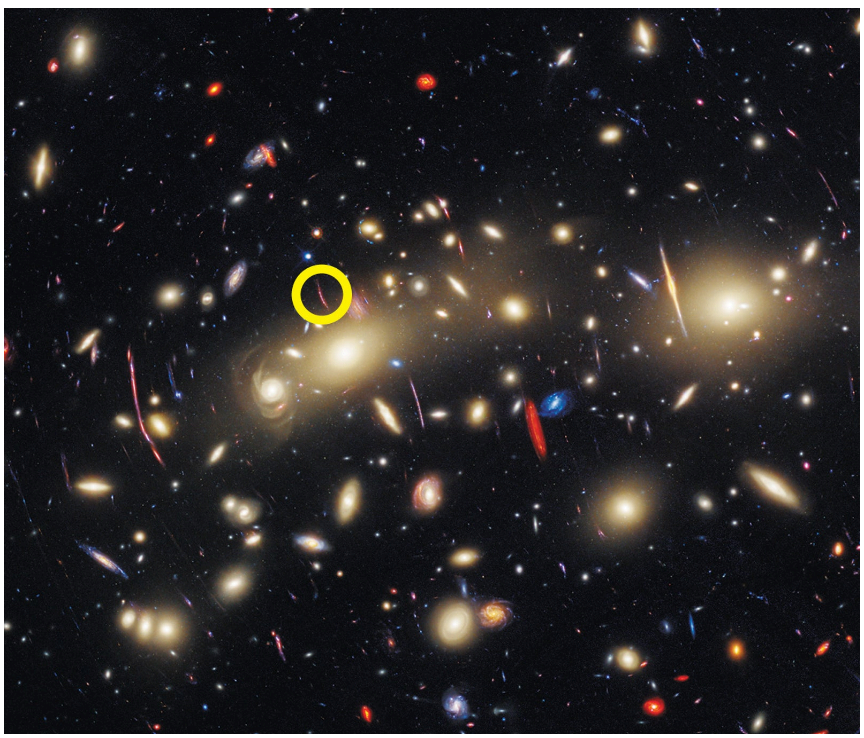
> Lensed stars can help us map the distribution of dark matter and reveal some of its properties.

Microlensing is produced mostly by stars in a galaxy cluster, but it can also arise from small concentrations of mass, including structures composed of dark matter. Microlensing can act as an additional lens in the cosmic microscope, increasing its power even further.

Icarus held the record as the most distant star ever observed for a few years, until the 2022 discovery of Earendel. This star—discovered by a team led by Brian Welch, then at Johns Hopkins University, and Dan Coe of the Space Telescope Science Institute—was found to be five times farther away. Of course, Icarus and Earendel are long gone; we are seeing them as they were billions of years ago because their light has taken that long to reach us. Earendel, for instance, appears as it existed when the universe was 7 percent of its current age. The estimated gravitational lensing magnification for Earendel is close to 10,000 times—the highest magnification observed so far. Earendel is the closest we have come to observing Population III stars, and astronomers think some of these original stars were still around at the time our observations of Earendel represent—so we may soon see them, too. Most likely, however, we will need to observe further back in time to see the first generation of stars.

Recent years have witnessed the discovery of tens of individual stars at extreme cosmic distances. On its journey to us, their light has crossed half the universe and gathered valuable information along the way. This light can tell us, for instance, about dark matter, a substance of unknown composition that permeates the entire cosmos. By far the most abundant form of matter in the universe, dark matter has evaded detection by the most advanced laboratories on Earth. It might be made of particles a tiny fraction of the size of an electron, or it might consist of black holes harboring masses comparable to the sun's. Regardless of what it is, dark matter virtually ignores ordinary matter (and our expensive detectors).

Fortunately for us, lensed stars can help us map the distribution of dark matter and reveal some of its properties. If dark matter in the gravitational lens forms invisible structures with masses comparable to or larger than those of planets, these structures will introduce a small but measurable change in the magnification of the lensed star. My team and I, now based at the Institute of Physics of Cantabria in Spain, have measured this type of anomaly in at least two lensed stars, named Godzilla and Mothra. This research revealed two invisible structures with masses in the range of tens of thousands to hundreds of millions of solar masses. If these structures are dominated by dark matter, they will rule out certain theories of dark matter under which it couldn't form such small structures. Future observations of these and other lensed stars can tell us more about what dark matter can and can't be.



An early star named Mothra (*circled*) appears in an ancient galaxy that existed three billion years after the big bang. The light from the galaxy and its stars has been warped and magnified by the mass of the galaxy cluster MACS0416, as seen in this image made with combined data from the Hubble and James Webb Space Telescopes.
NASA, ESA, CSA, STScI, Jose Diego (IFCA), Jordan D'Silva (UWA), Anton Koekemoer (STScI), Jake Summers (ASU), Rogier Windhorst (ASU), Haojing Yan (University of Missouri); Image

Processing: Joseph DePasquale (STScI)

Perhaps the most spectacular lensed stars we have discovered lie in the Dragon Arc galaxy, the first lensed galaxy ever observed, which was seen in the second half of the 20th century. The Dragon Arc isn’t extremely far from us—it’s “only” 6.5 billion light-years away. But many areas within the galaxy are magnified by factors exceeding 100, so we see the galaxy as it would look to a telescope 10 times larger than JWST. James Webb observed the Dragon Arc in 2023 and discovered more than 40 individual stars through their twinkles. Some studies of the stars in the galaxy suggest that dark matter may be composed of incredibly small particles, even lighter than the hypothetical axion predicted by quantum chromodynamics, a popular dark matter candidate. These studies also suggest that dark matter may have bizarre quantum properties that scientists call “fuzzy,” giving dark matter weird wavelike characteristics. At press time, JWST was poised to observe the Dragon Arc once more in search of new lensed stars to help answer these questions.

Using the latest telescopes along with nature’s lenses to observe ancient stars puts us in a new golden era of astronomy. JWST is regularly discovering distant stars, and new observatories are set to join it. NASA’s Nancy Grace Roman Space Telescope, to be launched in late 2026, will observe about 12 percent of the sky and should reveal thousands of new lensed galaxies at vast distances. Astronomers will then use JWST to observe the most promising candidates for harboring Population III stars in the hope that we can catch a primordial star near the region of high magnification.

Other space telescopes, such as the European Space Agency’s relatively new Euclid observatory, are monitoring even larger areas (about 30 percent of the sky) and are already uncovering myriad new gravitational lenses. Some of these lenses could be the first to reveal Population III stars when reobserved with JWST.

Even more exciting is the potential of a future NASA mission, the Habitable Worlds Observatory (HWO), which will have capabilities surpassing those of JWST in some ways. This supertelescope is still under consideration by NASA, and its final design and specifications have yet to be defined. Already, though, it promises an unparalleled opportunity to see the most distant stars. Many Population III stars, for instance, are thought to be very hot and might be too warm to be detected by JWST, which is better suited for cooler stars.

Our knowledge of the best natural gravitational lenses and the best magnified galaxies to observe will have advanced significantly by the time this new telescope is launched. Perhaps by then the first dinosaur stars will have already been confirmed, and we can study them in greater detail with HWO. These tools should help us extend our frontier even further back in time, closer to the beginning of the cosmos, revealing the universe’s first stars as well as our own origins.

José María Diego Rodríguez is an astrophysicist at the Spanish National Research Council (CSIC). He studies cosmology and the nature of dark matter.

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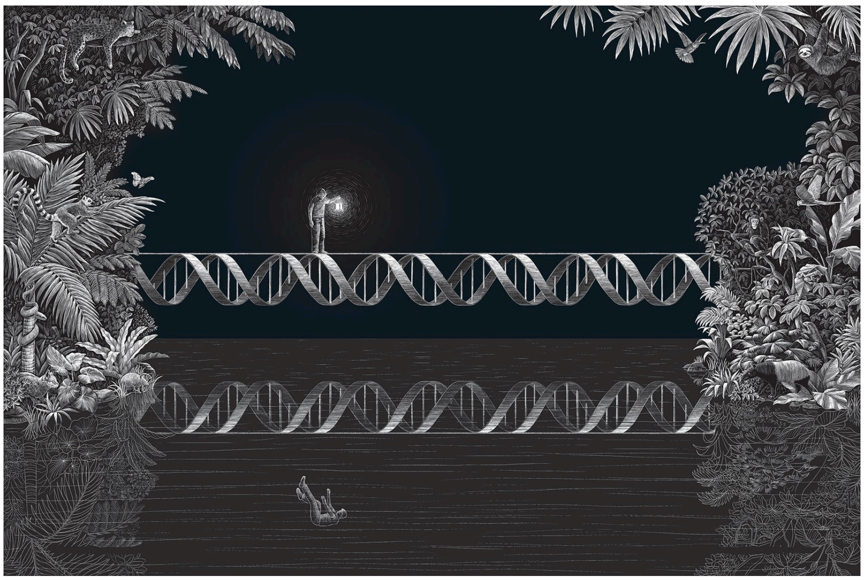
https://www.scientificamerican.com/article/jwst-could-finally-spot-the-very-first-stars-in-the-universe

Deadly ‘reverse’ cells can destroy us unless scientists stop them

Researchers are closer to making “reversed” cells that may wipe us off the planet

By Vaughn S. Cooper edited by Josh Fischman



Alex Boersma

Let’s say it’s 2036, and scientists are working on a new class of drugs. These medications are mirror-image versions of the molecules your body uses to fight disease. Their big advantage is that reverse compounds last longer in the body because destructive enzymes don’t recognize them and rip them apart. Yet the compounds are still effective against invading microbes. Clinical trials have been promising, and the team is eager to scale up production.

The researchers turn to engineered mirror bacteria—single cells made of reversed molecules—for the job. Bacterial factories aren’t a far-fetched idea. Today, for instance, pharmaceutical companies use bacteria to manufacture synthetic insulin for diabetics. Curious about whether mirror cells could be used in a similar way, the scientists experiment on a mirrored version of the common bacterium *Escherichia coli*.

Unfortunately, a researcher with a small cut on her thumb from dry skin forgets to put on her gloves and touches a surface contaminated with just a few of these cells. The bacteria get into her blood.

Her immune cells, which usually kill off intruders, don't recognize the mirror proteins on the novel bacteria and fail to react. The mirror microbes multiply and spread within her. Defensive antibodies never appear. After a few days at home, the scientist falls gravely ill. She's taken to a hospital, where she's loaded with antibiotics that can't make up for the massive failures of her immune system. Three days later she dies.

But while in her house, she had already spread the bacteria around. Her cat carries some into the garden, where they grow in the soil. Worms and insects become infected and transmit the mirror microbes throughout the neighborhood. Her children bring the bacteria to school. More and more people fall ill and begin to die. New outbreaks start in other locations as people and animals travel. A process of exponential and irreversible growth has begun—one that could quickly cover the world.

The scenario sounds like a sci-fi movie. But it is much closer to reality.

Scientists have been making rapid progress on technologies that could make it possible to build mirror organisms in the coming decades. Already biochemists can create increasingly complex mirror molecules, including enzymes that build mirror RNA. In the near future, similar enzymes could make reversed DNA. At the same time, synthetic biologists are getting closer to building regular bacterial cells from scratch. If progress in these two fields converges, it will be possible to build mirror bacteria.

A little more than a year ago I and 37 of my colleagues published a warning about this potential catastrophe in *Science*, insisting on a halt to this work. But how do we stop or control research that can take place in dozens of laboratories in many countries all over the world? This is the story of that challenge—and our plan to prevent a terrible future.

The first glimpse of that future emerged in 1848, when a young Louis Pasteur took the podium at the French Academy of Sciences in Paris and announced a remarkable discovery. Pasteur had been looking closely at the crystals of an acid found in wine. These compounds could take one of two forms that, despite being chemically identical—made of the same chemical building blocks and bonds—had opposite configurations. Hold your two hands in front of you, palms up. Their components are equivalent (four fingers, a thumb, a palm, etcetera), but they point in two different directions.

It turns out that almost all the basic molecules of life can exhibit this intriguing duality, as if one is the mirror image of the other. This property is called chirality. Other molecules, in contrast, are perfectly symmetrical; those are called achiral. Most large biological molecules are chiral, like our hands. No matter how you turn and twist molecules that are chiral opposites, you cannot make them overlap completely. But if a large group of people stacked their identically chiral left hands on top of one another, in the same orientation, the hands would overlap. Groups of chiral molecules are usually referred to as “left-handed” or “right-handed,” depending on which orientation they have in common. All life on Earth—everything that has descended from our last primordial common ancestor, which lived four billion years ago—builds its classes of molecules from only one of these two possible forms.

Nineteen of the 20 amino acids that make up proteins are left-handed, for instance, whereas DNA and RNA twist to the right.

> These microbes would have a strong claim to be the most dangerous biological threat ever known.

But there's no reason that mirrored versions of these building blocks can't exist, and indeed, many are found in nature. Although almost all amino acids are left-handed, right-handed amino acids D-alanine, D-methionine and D-leucine (the D prefix comes from the Latin *dextro*, meaning "right") appear in bacterial cell walls. Some others are being made in labs: right-handed versions of short amino acid chains are being synthesized as candidates for new drugs. As noted, their unusual orientation renders them resistant to enzymes that would otherwise latch on and destroy them. Astrobiologists have long thought life could have conceivably evolved in the opposite configuration—and, intriguingly, both left- and right-handed amino acids were found on the asteroid Bennu in approximately equal quantities.

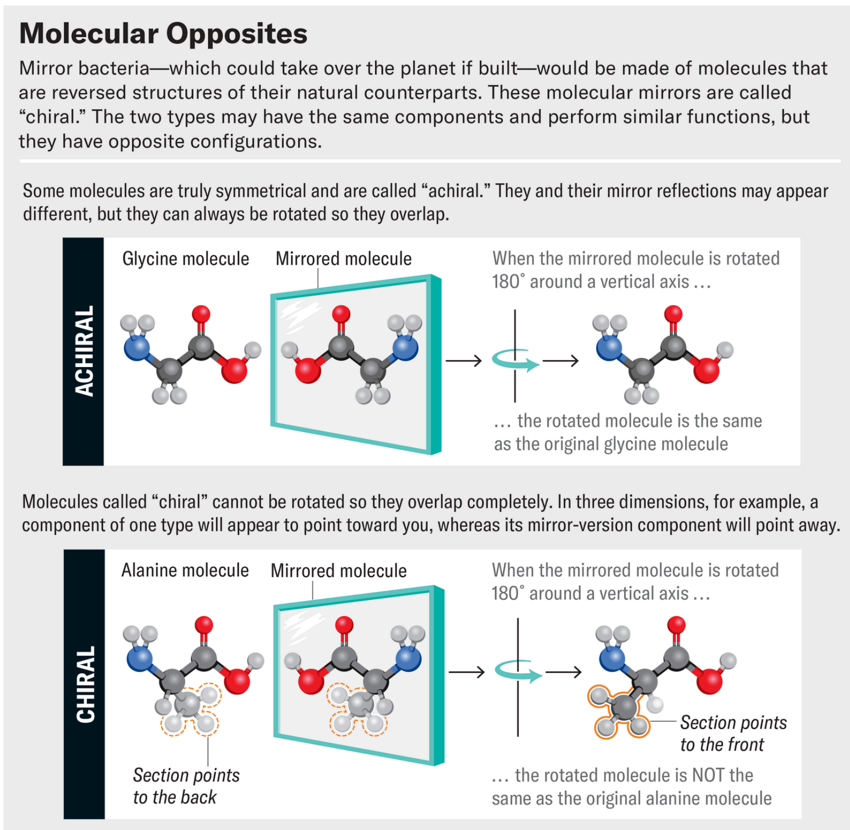
Scientists have already made a few mirror components. In 1993 researchers then at Johns Hopkins University reported making a right-handed version of the typically left-handed protein rubredoxin. More incremental work of this type has continued in the ensuing decades. Then, in 2022, other researchers announced they had built parts of a mirror-image enzyme that made a reverse RNA molecule. RNA is the essential template for most proteins, and it also plays crucial roles in numerous other processes essential to life. This engineering feat brought us much closer to making mirror components and assembling them into a functional mirror bacterial cell.

But it would be a killer mirror. Microbes like these would have a strong claim to be the most dangerous biological threat we've ever known. They could survive and grow on a range of naturally occurring nutrients in the environment. Yet they would probably be resistant to the many predators—viruses and protozoans—that keep populations of bacteria in check in the natural world. Such predators, after being selected during millions of years of evolution to recognize one protein shape, would not detect the opposite configuration. For the same reason, mirror cells could evade many parts of the immune system, causing infections likely to be fatal in people, animals and plants. They could spread and evolve rapidly in the environment, acquiring mutations that would enable them to grow on other nutrients, which would make them even more dangerous. And they could be impossible to eradicate, becoming a perennial source of infections that no human, plant or animal could fight.

When I first heard of this idea, about two years ago, I thought it must be science fiction. I figured the initially constructed mirror organism would be too fragile to live and reproduce. The closest things we have to synthetic life today are flimsy and delicate: test-tube-bound, not suitable for natural ecosystems and environmental pressures. Surely the mirror versions of artificial life-forms would be doubly so. For instance, what would they eat? Most of the molecular food sources that power life on Earth are chiral, too—wouldn't mirror bacteria need similarly oriented nutrients when they first escaped into the wild and starve if those nutrients didn't exist?

When some colleagues and I started to look into it, I learned that we were dangerously wrong. There are indeed many nutrients that mirror bacteria could digest, including many achiral symmetrical ones. Experiments have shown that populations of some natural bacteria, such as *E. coli*, can grow on *only* achiral nutrients, and mirror bacteria would be able to do the same.

Nor would a mirror organism necessarily be as fragile as the highly modified, close-to-synthetic cells we have today—cells like the ones my colleague John Glass's team at the J. Craig Venter Institute has constructed with a minimal number of genes or organisms like those that George Church's group at Harvard University has "recoded" with slight alterations in their DNA. These are the product of thousands of engineering steps that make them much more delicate than bacteria that thrive in the environment. In contrast, mirror bacteria could be identical to robust natural bacteria in all ways but one, confounding our intuitions about the fitness of engineered life outside the lab.



Brown Bird Design; Source: *Technical Report on Mirror Bacteria: Feasibility and Risks*, by Katarzyna P. Adamala et al.; December 2024 (*primary reference for graphic*)

What would happen if mirror bacteria got even a tiny foothold in the natural environment? The result could look a lot like the work of my mentor, evolutionary biologist Richard Lenski of Michigan State University. He has conducted experiments in which a dozen cultures of naturally chiral lab-grown *E. coli* are given a fresh glucose meal every morning. He found that even genetically identical microbes would quickly evolve and diversify, becoming distinct communities.

My work with infectious bacteria has shown that permanent and meaningful diversification may require only hundreds of generations. Mirror bacteria could evolve in the same way. It wouldn't be a one-and-done event: you'd create a second tree of life that would trace its own evolutionary paths through diverse ecosystems, finding niches wherever it could. An accidental release could cross an irreversible threshold.

People would be on the wrong side of that passage. Ordinarily, the trillions of bacteria living in our gut provide an early defense against normal-chirality pathogens: some produce antibacterial molecules that directly inhibit or kill pathogens, and some help to trigger immune responses such as the production of antimicrobial peptides or antibodies. But if you ingested mirror bacteria, many of these defenses would likely fail.

Your gut's microbiome probably wouldn't be able to spot mirror bacteria's reversed molecules, so it won't trigger the production of antibacterial compounds. Even if they were produced, these substances almost certainly wouldn't be able to bind to mirror molecules, just as a left glove doesn't fit on a right hand. Perhaps worst, the failure of these early defenses means it's unlikely your body would trigger the downstream immune responses required to successfully fight off an infection.

Our immune systems have evolved complex and layered immune responses to bacteria, recognizing the molecular signatures (called pathogen-associated molecular patterns) that are common to many of them and triggering immune responses to limit their invasion. Our bodies would be unlikely to spot invaders with reversed molecular structures. Even if they did, they wouldn't be able to attack the microbes with their full arsenal of immune defenses, many of which also rely on chiral interactions.

For example, one critical early part of the immune response is the activity of cells such as neutrophils and macrophages, which "eat" bacterial threats and digest them by attacking chiral bacterial molecules with a chiral enzyme. Their digestive enzymes wouldn't be able to break the chemical bonds of mirror cells, because they have evolved to grab and break those cells' opposites. It's likely that macrophages and other immune cells would be less effective at killing mirror bacteria.

That's only one problem. Your immune system also has an adaptive system of specialized immune cells and antibodies that attack and destroy invading microbes. This system remembers what those intruders look like so it can mount a stronger response if the threat returns.

Such adaptive immune memories rely on chiral molecules. We can't directly study what a mirror-bacterial infection would look like, but the diseases of people born with genetic defects in parts of the immune system provide clues. One such group of patients has a dysfunctional form of a receptor called MHC-II. Normally this receptor captures fragments of pathogens and signposts them for T cells, but the receptor doesn't work properly in these patients. Similarly, mirror proteins could not be broken down into those fragments, so MHC-II would not be able to signpost them. Mirror infections therefore might resemble the infection of an MHC-II-deficient patient.

The comparison is not reassuring. These people often die in childhood, overwhelmed by infections caused by the common bacteria and viruses all around us. And this is a case study of failure in just *one part* of the immune system. Mirror bacteria would probably evade several parts at the same time.

The concern is that, freed from the pressures of immune constraints and the competition of the natural microbiome on our skin and in our gut, mirror bacteria could replicate faster than they are cleared and then, riding the bloodstream, deposit bacterial cells throughout the body. The inside of the human body has enough achiral nutrients for mirror bacteria to grow. A mirror bacterium engineered to use a natural-chirality diet would fare even better. The body would then become a petri dish, like a cadaver—unprotected by living immune cells. What this strange infection would look like precisely is unclear, but the expected result is sepsislike inflammation and death.

> As the danger of mirror cells became more apparent, a team of scientists began working on what to do.

Astonishingly, it gets worse. The natural world is full of bacteria—a million cells in a gram of seawater, a billion in a gram of soil. They don't overwhelm the planet, because they have predators that rely heavily on chiral processes. Viruses called bacteriophages enter bacteria by latching onto surface proteins that they match the configuration of like a key fitting into a lock. The phages kill bacteria, limiting their threat. But if there is no match between a phage and a surface protein, the phage can't get in. Even if one did get inside a mirror bacterium, none of its replication machinery or genetic material would work there. The bacteriophage would be stuck, alone and isolated, incapable of replicating inside the cell.

Amoebas and other microbial predators, meanwhile, track and swallow bacteria and digest them whole. They'd face the same problems as macrophages in the human immune system: they would be less able to detect mirrored molecules, and even if they managed to swallow one, they'd probably struggle to digest it and use the mirror component parts as nutrients. Even at larger scales—those of plants and other animals—immunity consistently relies on chiral interactions. As a result, many animal and plant species might be unable to fend off mirror bacteria.

There could also be enormous environmental consequences. Cyanobacteria are simple organisms that derive nutrition directly from sunlight and carbon dioxide, and they often don't require any chiral nutrients. The same would be true for mirrored versions if any were built. But because they would probably be resistant to viruses, there would be much less downward pressure on their populations. As they grew in number, they would compete with other bacteria for scarce ocean nutrients such as iron or phosphorus, significantly reducing the population of natural-chirality bacteria, which would leave species such as marine krill with much less to feed on. If krill populations collapsed, that could in turn drive many larger species such as whales to extinction.

How do we stop this? As the steps toward danger became more apparent in the past several years, a team of more than 150 scientists in different disciplines assembled from around the world and began working to figure out what to do. We gathered in Paris last June to make a plan.

The agreement among researchers in Paris was widespread: mirror organisms should never be created. Laws will be needed to ensure they aren’t, and we must draw red lines around the most dangerous technologies that could enable their synthesis. In the meantime, research funders can help by confirming they won’t support work aimed at building mirror cells—much as they have already committed to not funding research into human cloning.

I started out confused and dubious about this threat, and then I became very concerned. But today I find myself invigorated about our ability to ward off catastrophe—because we’ve spotted this threat so early.

Yes, scientists have made small chiral molecules. But making a complete, functional mirror cell would take extraordinary effort: synthesizing longer and longer biomolecules, making a bacterial chassis from scratch, and creating all the component parts of cellular life, such as ribosomes. Then everything would have to be assembled into a living, working cell. Despite decades of work since the early 1990s, nobody has built an entire standard cell from scratch. We estimate it would require the kind of effort and resources of scientific megaprojects such as the Human Genome Project—which has cost billions of dollars—to make a completely new entity such as a mirror microbe. Building mirror bacteria is a bit like building a skyscraper twice the height of today's tallest structures: we know technically what needs to be done, but it would be an extremely complex feat of engineering. This fact gives us a golden opportunity to tackle the risk long before it materializes.

Acting now is our leverage. There aren't many examples of scientists identifying issues with the development of technology *before* issues emerge. Chlorofluorocarbons were retired from use only after they'd torn a hole in the ozone layer. Thalidomide stopped being prescribed for pregnant women only after thousands of infants were born with birth defects. But we have identified this problem.

In addition to a moratorium on mirror-cell work, we can develop strong modes of governance with international entities that identify and control the chemical constituents of mirror molecules and cells. These agencies could spot whether a lab or a country was accumulating unusual amounts of these compounds, just as they sound the alarm today if a country is stockpiling the components of chemical or nuclear weapons.

Yet we don't want to limit science in this area completely. Some research in synthetic biology could help with the design and manufacture of novel drugs that could benefit the world. For instance, it may be a good idea to allow scientists to work with certain small mirror molecules but ban the stockpiling of mirror compounds that exceed a certain length. The longer ones can be more easily used to assemble an entire mirror cell.

We won't figure out where to draw the line or how to solve all these challenges in one go. We can't make any final decisions on an issue of this importance at any single conference. Much more work is needed to understand the best governance methods that will ensure that the risks can be avoided. But I’m tremendously encouraged by how quickly a large group of scientists and biosecurity experts—more than 300 people attended the Paris meeting either in person or virtually—recognized there was a huge problem and agreed on the urgency of finding a solution.

The risks of this technology are great, but it’s easy to see the people who are working hard to eliminate them. All we have to do is look in the mirror.

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https://www.scientificamerican.com/article/lifes-evil-twins-mirror-cells-could-doom-earth-if-scientists-dont-stop-them

The hidden threat eating away at museum treasures

Extremophile molds are invading art museums and devouring their collections. Stigma and climate change have fueled their spread

By Elizabeth Anne Brown edited by Kate Wong

Maja Lindholm Kvamm, curator and collections manager at the Roskilde Museum in Denmark, cleans objects in a storage facility that has been sealed off since 2014 because of a mold outbreak. Ty Stange

Last summer I polled the great art houses of Europe with a seemingly straightforward question: Had they had any recent experiences with mold in their collections?

Mold is a perennial scourge in museums that can disfigure and destroy art and artifacts. To keep this microbial foe in check, institutions follow protocols designed to deter the familiar fungi that thrive in humid settings. But it seems a new front has opened in this long-standing battle. I'd recently heard rumblings that curators in my then home base of Denmark have been wrestling with perplexing infestations that seem to defy the normal rules of engagement. I wondered how pervasive the problem might be.

My survey did not make me popular. Some museums responded quickly—too quickly, perhaps, to have checked with their curators. Ten minutes after receiving my inquiry, the press office at the Uffizi Gallery in Florence assured me unequivocally that there was *no mold at the Uffizi*. The museum declined to connect me with the curatorial team or restoration department. Many institutions—the Louvre, the British Museum, the Musée d'Orsay—didn't respond to my calls and e-mails at all. I eventually came to suspect the Vatican Museum had blocked my number.

Frustrating though it was, this is the reception I expected. Asking a curator if their museum has problems with mold is like asking if they have a sexually transmitted disease. It's contagious, it's taboo, and it carries the inevitable implication someone has done something naughty.

Consequently, mold is spoken of in whispers in the museum world. Curators fear that even rumors of an infestation can hurt their institution's funding and blacklist them from traveling exhibitions. When an infestation does occur, it's generally kept secret. The contract conservation teams that museums hire to remediate invasive mold often must vow confidentiality before they're even allowed to see the damage. But a handful of researchers, from in-house conservators to university mycologists, are beginning to compare notes about the fungal infestations they've tackled in museum storage depots, monastery archives, crypts and cathedrals. A disquieting revelation has emerged from these discussions: there's a class of molds that flourish in low humidity, long believed to be a sanctuary from decay. By trying so hard to protect artifacts, we've accidentally created the "perfect conditions for [these molds] to grow," says Flavia Pinzari, a mycologist at the Council of National Research of Italy. "All the rules for conservation never considered these species."

These molds—called xerophiles—can survive in dry, hostile environments such as volcano calderas and scorching deserts, and to the chagrin of curators across the world, they seem to have developed a taste for cultural heritage. They devour the organic material that abounds in museums—from fabric canvases and wood furniture to tapestries. They can also eke out a living on marble statues and stained-glass windows by eating micronutrients in the dust that accumulates on their surfaces. And global warming seems to be helping them spread.

Most frustrating for curators, these xerophilic molds are undetectable by conventional means. But now, armed with new methods, several research teams are solving art history cold cases and explaining mysterious new infestations.

Rust-colored stains have been present on Leonardo da Vinci's most famous self-portrait, drawn in red chalk on paper, since at least the 1950s. Researchers have determined that the culprit is the xerophilic fungus *Aspergillus halophilicus.*
Photograph of a drawing by Leonardo da Vinci by Ann Ronan Pictures/Print Collector/Getty Images

The xerophiles' body count is rising: bruiselike stains on Leonardo da Vinci's most famous self-portrait, housed in Turin. Brown blotches on the walls of King Tut's burial chamber in Luxor. Pockmarks on the face of a saint in an 11th-century fresco in Kyiv. It's not enough to find and identify the mold. Investigators are racing to determine the limits of xerophilic life and figure out which pieces of our cultural heritage are at the highest risk of infestation before the ravenous microbes set in.

Scandinavian museums have been some of the first to confront the effect of climate change on molds. Whereas certain parts of the planet are growing drier as temperatures rise, the Nordic countries are among those that are becoming wetter. Higher temperatures allow the air to hold more moisture, and extreme rainfall events called cloudbursts are occurring more frequently. Sea-bound Denmark, for example, which is already rainy, could receive more than 50 percent more winter rainfall by the end of this century.

In decades past local museums in Denmark could get away with storing their treasures in drafty basements, sheds and even barns—practices that are typical for small museums around the globe when funding is limited and they don't have the luxury of purpose-built facilities. But rising humidity and increasing floods led to runaway mold infestations at several Danish institutions in the 2000s. In response, Danish museums invested tens of millions of dollars to develop centralized, climate-controlled storage facilities.

It's a pattern that's playing out in many parts of the world. As the climate becomes more erratic, museums are tightening the temperature and humidity controls for their collections to prevent mold growth. But paradoxically, these efforts may be creating the perfect niche for a different kind of mold.

In 2012 Danish museum conservator Camilla Jul Bastholm was patrolling one such climate-controlled facility—a newly retrofitted warehouse about an hour outside Copenhagen—when she spotted subtle white shimmers on a variety of items, including hats and cloaks. "It was tricky to see with the naked eye," Bastholm says of the discoloration—"a whitish, brittle layer on the surface of the artifacts."

Conventional wisdom would have suggested that these shimmering patches were pesticide blooms, an unfortunate legacy from past generations of conservators who sprayed their collections with pesticides such as DDT to keep insects and molds at bay. These chemicals absorbed into artifacts only to bubble up to the surface later in the form of white blotches. But Bastholm had seen these little white dots before. She was working in another repository as a contract conservator, the kind of consultant museums hire after a flood or leak. After eight hours in that facility, a colleague had “reacted like she had the beginning of the flu—her eyes running; she had a migraine.” To Bastholm, that sounded like exposure to a fungus, not a chemical.

A close examination revealed that about half of the objects in the Roskilde Museum’s facility bore these worrisome white marks. Two museum employees developed the same flulike symptoms Bastholm had observed before. The staff were convinced they had a mold outbreak. Yet the building’s envelope was intact, with no evidence of leaks.

Hats from Denmark’s Roskilde Museum that have been stored in a climate-controlled warehouse outside Copenhagen exhibit shimmery, whitish patches from xerophilic molds.
Trine Sejthen

Twice, museum leadership called in outside technicians to test for mold, a process that involves rubbing samples of potentially contaminated material onto a fungal growth medium—a gelatinous goo packed with nutrients and moisture to jump-start mold growth in a petri dish. The dishes bloomed black, yellow, brown and green with common molds, but nothing matched the enigmatic white marks.

When Bastholm became the Roskilde Museum's lead conservator in 2014, she ordered the facility—with its tens of thousands of historical objects—closed to all but essential traffic while she tried to solve the mystery. Three years later Bastholm got her first break. A Dutch mycologist who specializes in molds that affect food production suggested she cook up a very unusual fungal medium: a petri dish environment that would *kill* most fungi. When she cultured the samples on this inhospitable medium, with far too little water available to sustain most molds, her petri dishes suddenly looked like snow globes, covered with shimmering white flakes. Genetic analysis revealed they were four related species of xerophilic molds in a group known as *Aspergillus* section *restricti*.

Around the same time Bastholm discovered the xerophile outbreak in Denmark in 2012, Flavia Pinzari, then a biologist at the Italian Ministry of Cultural Heritage in Rome, was investigating a fungal mystery of her own. Pinzari had been monitoring mold infestations at libraries and archives in Rome, Genoa and Modena over the previous decade. Staff reported feeling ill, and small white dots peppered ancient manuscripts and book bindings at six institutions—among them the Bibliotheca Angelica in Rome, Europe's oldest public library and one of the world's great collections of rare and ancient books. She wondered whether a classic conservation technique could be inviting a stealthy class of fungi into the collections.

In the 1600s the Bibliotheca Angelica was run by Augustinian friars, an order of religious scholars that the pope charged with determining which texts would become *libri prohibiti*—forbidden books destined for the Catholic Church’s bonfires of heretical material.

Texts on astrology, alchemy, science and unorthodox religious thinking passed through the Augustinians’ hands. “The Augustinians studied them and censored them, but they did not destroy them,” Umberto D’Angelo, former director of the Bibliotheca Angelica, said in a press release. “Fortunately for us, they are all still here.” Today the Bibliotheca’s holdings include exquisite 11th-century illuminated manuscripts, one of the earliest copies of Dante’s *Divine Comedy*—and all those precious *libri prohibiti*.

The infestations Pinzari observed were unusual because they were happening in institutions with, as far as she could tell, adequate climate control. The only factor connecting the six infestations was the institutions’ use of mobile shelving systems called compactus units, refrigerator-size shelf blocks that slide on rails. Compactus units have been a fixture of museum and library storage since the 1950s because they save space and have an airtight seal, protecting their contents from invasive dust and mold spores.

Pinzari couldn’t get any of the white molds to grow on any fungal media. But she did have access to a high-powered microscope. Peering through the viewfinder, she saw fibrous tendrils with a riot of hairs—the signatures of *Aspergillus* section *restricti*.

In 1993 Japanese microbiologist Hideo Arai used special fungal growth media to identify the mold that has caused extensive staining on the walls of King Tut’s burial chamber. The brown blotches are the result of an *Aspergillus penicilloides* infestation.
DeAgostini/S. Vannini/Getty Images (*top*); DeAgostini/G. Dagli Orti/Getty Images (*bottom*)

How the mold might find a home in the compactus shelves was a mystery at the time. But in the decade since, Pinzari and other researchers have started to learn how these xerophilic species thrive where other molds can’t. They seem to remodel their environment, turning desert into oasis one tiny inhospitable patch at a time.

Take *Aspergillus halophilicus*, one of the species behind both the Danish infestation and the Italian library outbreaks. Once a spore of *A. halophilicus* lands, Pinzari says, it sends out exploratory tendrils called hyphae that twist through cracks and crevices to search for nutrients. “It’s looking for water,” Pinzari explains, but if none is forthcoming, it’ll settle for salt crystals.

Salt crystals are extraordinarily effective at absorbing moisture from the air. That’s why the contents of your saltshaker will turn into a solid block unless you put rice in it. *A. halophilicus* can collect salt from the environment and re-excrete it in the form of a salt-rich exopolymer—a kind of briny jelly that covers its hyphae. Researchers hypothesize that the exopolymer prevents the mold’s tissues from drying out and helps the mold maintain a layer of humid air in its immediate vicinity.

Pinzari believes that by trying so hard to control conditions inside compactus shelves, collection managers have accidentally handed the reins over to xerophilic fungi. With no airflow to disrupt their tiny artificial atmospheres, the molds have been able to reshape their surroundings to suit their needs. Ironically, artifacts might have been better off in those drafty Danish barns.

From a conservator’s perspective, there’s lots to worry about in a xerophile’s remodeling plans. Sometimes xerophilic or xerotolerant fungi eat a museum artifact directly—munching on the egg-based tempera in a fresco, the cotton canvas of a painting or even the salty flesh of mummies.

Other times the spores land on something the mold can’t directly consume, such as metal, glass, rubber, plastic or limestone. But some of the *restricti* species are “capable of living on almost nothing,” Pinzari says, surviving off the nutrients in motes of dust. In these cases, damage to artifacts is collateral, resulting from the mold’s remodeling activities and digestive processes and from the dying off of the hyphae.

That's what researchers think happened at St. Sophia's Cathedral, a 1,000-year-old holy site in Kyiv that has been described as the soul of all Ukraine. In 2010 brown blotches began to pockmark the cathedral's precious 11th-century frescos, starting with the altar to the martyr St. Sophia. "It's very painful because people love this cathedral very much," says Marina Fomina, a microbiologist at the National Academy of Sciences of Ukraine.

> In 2025 Camilla Jul Bastholm received messages from institutions around the world that have experienced mold infestations they expect might be xerophilic but haven't necessarily been made public.

The saint's breakout came as a surprise on two counts. Not only has the cathedral been climate-controlled since the 1950s, but its wall paintings are buon frescos, meaning they were made of mineral compounds that contain no organic materials for mold to live on.

Fomina reached out to Pinzari after reading about her skirmishes with xerophiles in the Italian libraries. On Pinzari's advice, Fomina tried to culture mold from the frescos on special fungal growth media. Nothing grew. The Ukrainian team was so alarmed about the damage that it arranged for costly molecular genetic analysis of samples from the paintings, which confirmed the presence of *A. halophilicus*.

To understand what was happening to the frescos, the managers of the cathedral gave Fomina permission to cut out some mold spots from a section of the fresco that had been restored in the 1950s. Under the microscope, she saw the unmistakable shape of *A. halophilicus*—it can resemble a tangle of spaghetti with fine, downy hairs—tunneling between layers of plaster, causing the surface of the fresco to crumble and flake. But curiously, these hyphae appeared to be covered with tiny crystals, like rock candy.

It seems that when *A. halophilicus* is surrounded by calcium, as in the chalky plaster, it secretes organic acids that turn calcium ions—which appear to be harmful to the mold—into benign crystals of calcium malate. The dark spots themselves were another by-product of this protective mechanism. The higher the concentration of the calcium minerals, the darker the mold's pigments become, Fomina explains.

Xerophilic fungi aren't entirely new to museums and cultural heritage sites. Italian archivists in the mid-1900s described outbreaks identical to the ones Pinzari observed, and orange stains that have been present on da Vinci's most famous self-portrait since at least the 1950s have since been conclusively attributed to *A. halophilicus*. But it wasn't until decades later that researchers began routinely using growth media with low levels of water available for microbial processes to coax out xerophilic fungi. One of the first to adopt these low-water activity media to test for elusive fungi on cultural items was Japanese microbiologist Hideo Arai, who used them to isolate mold on hemp-paper paintings in Byōdo-in Temple in Uji, Japan, in 1984. Later, in 1993, Arai used these specialized media to identify *Aspergillus penicilloides* as the culprit behind an infestation on the walls of King Tut's burial chamber. The dark blotches from the mold had vexed researchers since soon after archaeologist Howard Carter opened the tomb in 1922.

Yet despite such high-profile cases, experts still believed that true xerophilic infestations were rare, a notion that persisted because the tools to detect them were so hard to obtain. Even today, decades after Arai's pioneering work, access to these low-water activity media is extremely limited. "You can't buy them industrially—nobody produces them," Bastholm says. "If you want to detect these xerophilic fungi, you have to collaborate with research laboratories."

Curators from the Roskilde Museum inspect objects in the museum’s storage facility for mold.
Ty Stange

What’s more, some species are so persnickety that even low-water activity media won’t do the trick consistently. Fomina and her colleagues still haven’t been able to cultivate samples in the lab from the St. Sophia infestation, despite more than 10 years of trying. They keep at it because until scientists discover what makes a xerophile feel at home in a petri dish, there won’t be tests that museums can use to catch them without resorting to genetic testing that many institutions can’t afford.

Fomina and Pinzari suspect that part of the reason *A. halophilicus* is so hard to culture is that it may already be dead by the time conservators notice the infestation. Often found together with other xerophilic species, *A. halophilicus* seems to work as a pioneer: it arrives in an inhospitable environment and does its extraordinary DIY, and then other, less industrious molds swoop in to take advantage of the better growing conditions—potentially using dead *A. halophilicus* tissues as a resource to jump-start their own growth.

That’s how xerophilic fungi seem to have flown under the radar for so long. When a moldy artifact is swabbed on conventional, high-water activity media, only garden-variety fungi grow. Museums assume they’ve done something wrong with the storage—that humidity had risen higher than they realized, or a leak went undetected—and keep the matter under wraps, for fear of looking careless. The xerophilic molds elude detection and continue to wreak havoc. The problem “is much more diffuse than we might think,” Pinzari asserts.

Once a museum identifies a mold infestation, it faces the difficult question of how to stop it. Through the 1970s conservators deployed biocides, chemicals—including antibiotics and formaldehyde—that wipe out microbes indiscriminately. That’s what experts used in 1963 when green algae threatened the 17,000-year-old depictions of aurochs, horses and deer found in France’s famed Lascaux Cave. But just as broad-spectrum antibiotics can wreak havoc on the human gut by eliminating good bacteria along with the bad, biocides can open the door to even more harmful microbes by clearing out the competition.

Scientists think decades of treatment with biocides in Lascaux led to the proliferation of a fungus called *Fusarium solani* that covered the cave like snow in a matter of days. The biocides are also thought to have allowed antibiotic-resistant strains of bacteria and fungi to grow unchecked in the cave, as well as pigmented fungi that left permanent dark stains on the Ice Age images. In Europe, the use of biocides is now tightly restricted.

One of the only options for large-scale infestations—for example, in libraries and archives—is fumigation. But some of the substances used in fumigation leave residues that can eventually degrade the material, says Katherina Derksen, a painting conservator and microbiologist at the Academy of Fine Arts in Vienna. Some of these chemicals can also pose a risk to human health.

When a mold’s takeover of an artifact must be stopped, there’s gamma radiation—pelting it with electromagnetic energy from radioactive decay to kill fungi and spores. But this technique penetrates deeply and can extensively damage materials. In some cases, “you lose both microbes and the object you’re trying to save,” says Katja Sterflinger, a geomicrobiologist and heritage scientist at the Academy of Fine Arts in Vienna.

That leaves conservators with only a basic tool kit for containing a fungal outbreak: quarantine infested objects, vacuum off the worst of the mold, and treat affected items with ethanol when possible. That’s what they ultimately had to do at the Roskilde Museum, the Danish institution where Bastholm found the xerophiles.

In 2023, nine years after Bastholm closed off the Roskilde Museum’s storage facility, the museum’s governing board decided it was time to reclaim the place. “We’ve been afraid of it,” says Isabella No’omi Fuglø, the museum’s chief of collections. In 2025, after two years of strategizing, a small group of conservators finally suited up in protective gear and headed into the mold-ridden warehouse.

One day last fall I donned a mask and protective clothing to tour the storage facility, then several weeks into its rehabilitation. My guide was curator and collections manager Maja Lindholm Kvamm. Kitted out in a white cloth jumpsuit and respirator, with an industrial-grade vacuum in tow, she looked like a Ghostbuster in an astronaut helmet.

Over the course of the summer Kvamm and a team of about 15 people, including student assistants from a local conservator’s school, had handled more than 100,000 objects—from oyster shells to paintings and carriages—inspecting them for mold and scraping off the dirt and dust of the ages.

Kvamm says they were relieved to find the museum’s archaeological treasures—among them stone age relics and Viking artifacts discovered by hobbyist metal detectorists—were largely spared from contamination, although the same couldn’t be said for the boxes containing them. But other items were beyond saving or too fragile to clean with conventional means. “A big part of the cleaning process is figuring out what the object can handle—even just being touched,” Fuglø says.

A team of 15 conservators and assistants examined and cleaned some 100,000 objects from the Roskilde Museum’s collections last summer.
Ty Stange

As I wandered aisles stacked high with boxes of paintings, antique furniture and the occasional Viking age skeleton, I found several parcels wrapped in plastic and labeled “SKIM!!!”—short for *skimelsvamp*, “mold” in Danish. Inside one was fish skin so riddled with mold “it was basically alive,” Kvamm recalls. It falls to Kvamm to determine what mold-damaged objects are worth the effort to stabilize and restore, she explains. “Is the story [behind the object] interesting enough? Do we know where it’s from? Do we have similar objects?”

Disposing of a mold-eaten object in a museum’s collection is a bureaucratic nightmare. “You have to ask other museums if they might be interested,” Kvamm explains. “You have to [try] to track down the person who donated the item and ask them if they want to have it back.” Once those hurdles are cleared, she anticipates a multimonth dialogue with the Ministry of Culture before she will finally be allowed to do away with her gross fish skin.

For moldy items in the Roskilde Museum collection that are deemed salvageable, Kvamm makes several passes with her vacuum hose interspersed with gentle scrubbing with a brush. She then caps off those efforts with a judicious spritz of ethanol.

But even the objects that have no signs of mold receive the tender ministrations of Kvamm and her team. They delicately wipe off motes of dust to make it harder for mold to take up residence again. “We don’t have anything else we can do now but clean it and then just keep checking on it,” Fuglø admits.

To figure out better ways to prevent and treat xerophilic mold infestations, scientists need a better understanding of the molds’ basic biology—namely, the conditions under which they falter and thrive. To that end, Sterflinger and her team in Vienna are busy trying to determine just how little water xerophilic molds can survive on. Yet even if researchers do identify a moisture level that’s safe from xerophilic molds, Sterflinger says it’s untenable to bring overall humidity levels in storage facilities down much lower than they already are: climate control is expensive and a major source of greenhouse gas emissions, which museums are under pressure to curb.

Instead they’ll have to determine which materials are most vulnerable to xerophilic and xerotolerant molds, Derksen says. That way collection managers can decide which items need more stringent and energy-intensive storage conditions. Future storage facilities could designate a small space with the tightest climate control for more sensitive objects, she says.

Derksen is conducting mold censuses in “healthy” museums without infestations so they can develop surveillance techniques that will detect surges in particular mold species before they’ve reached a level visible to the human eye.

The researchers agree we need to learn all we can from the organisms found in the artificially extreme environments of museums. The lessons aren't just relevant to art conservation. These weird species—some of which are new to science—are likely to pop up in other places that people are trying to keep unnaturally sterile.

Xerophilic fungi have infested food-production facilities from Belgian chocolate factories to meat-curing operations in Italy. In 2024 an infestation of *Aspergillus flavus*—a xerophilic mold species involved in some museum outbreaks—was discovered in Denmark's biggest hospital, sickening pediatric cancer patients and contributing to several deaths, including that of an 11-year-old boy. Xerophilic molds can colonize human tissue in immunocompromised people—doctors found colonies of *Aspergillus fumigatus*, another mold involved in museum infestations, in one Danish woman's brain, chest and lungs after she had been treated for leukemia in the contaminated wards. Other scientists hope to put the xerophiles' remodeling powers to good use, deploying them to break down pollutants and sequester harmful metals.

The museum mold hunters are thankful for the institutions taking them into their confidence. Letting go of the shame is the only way we can learn about these molds, Pinzari says. Bastholm says that in 2025, she received a flood of messages from institutions around the world that have experienced mold infestations they suspect might be xerophilic but haven't necessarily been made public—from across Europe, the U.S., Pakistan, Israel and Asia. Still the stigma remains strong. None agreed to be interviewed on the record for this article.

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https://www.scientificamerican.com/article/how-extremophile-molds-are-destroying-museum-artifacts

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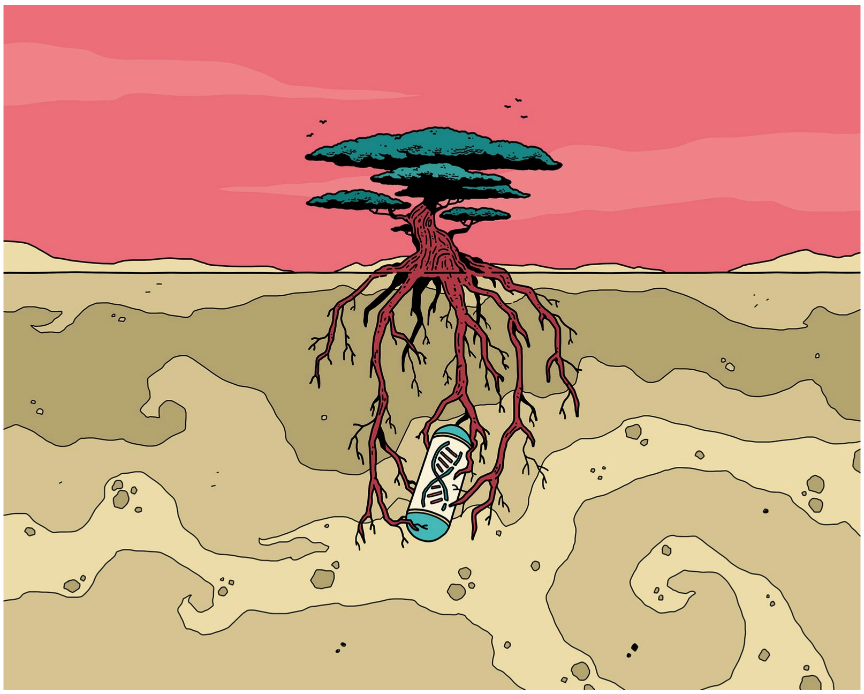
Can a time capsule outlast geology?

A ridiculous but instructive thought experiment involving deep time, plate tectonics, erosion and the slow death of the sun

By Peter Brannen edited by Seth Fletcher



Federico Tramonte

This article is part of a package in collaboration with Forbes *on time capsules, preserving information and communicating with the future. Read more from the report.*

Stuff is old where I live, in greater Boston. Clapboard houses that list with age bear plaques touting the former residence of the town cordwainer or victualler. The gravestones, worn rough by New England winters, also stand crooked, bearing similarly outmoded biblical names—a Lemuel here, an Ephraim there. Old, too, are the local churches where many of these souls were commended to the great hereafter.

As for the building material that makes up these churches, well, that's a little bit older still. Roxbury puddingstone, the mottled rock quarried nearby and used for much of the old church masonry in Boston, formed 600 million years ago in violent submarine landslides off the coast of a barren volcanic microcontinent that had been rifted off Africa. This upheaval happened so long ago in the course of the perpetual wandering of continents that the whole thing took place somewhere near the South Pole. The sediments hardened to rock, then hitched a ride across a bygone ocean as part of a traveling tectonic plate before being sutured onto the rest of equatorial North America some 140 million years before the first dinosaur evolved.

This rock now pokes out from underneath fallen leaves and the edges of Dunkin' parking lots in the Boston area. Very little else here has survived the intervening half-billion-year eon, save a superficial veneer of glacial till from the extremely recent last ice age—one that is surely doomed in the next few dozen millennia or so. Had somebody hoped to leave a time capsule for today's Bostonians 250 million years ago in the Triassic period, or even four million years ago in the Pliocene epoch, they would have been completely, utterly screwed. The same is true for anyone aspiring today to send such an envoy into the geological deep future. Ephraim and Lemuel's mortal remains, much less the local Dunkin', will not survive into geological time. "Can any mountains, any continent, withstand such waste?" Charles Darwin wrote in his 1839 book *The Voyage of the Beagle*, referring to the defacing forces of erosion.

Mindful of my eon-old local rock and having been charged by *Scientific American* with figuring out how far into the deep future one could even hope to send a time capsule here on Earth, I stumbled on the humbling work of stratigrapher Steven Holland of the University of Georgia. I reached him at his office, and he gamely decided to play along with my thought experiment.

“Something like [five to 10 miles] of rock is gone above me right now,” Holland said, marveling at the vanished local mountains that should entomb his office deep within Earth. Their disappearance has much to tell us about the ravages of deep time. As Pangaea assembled from once disparate continents around 300 million years ago, the Maghreb, encompassing present-day northwestern Africa, headbutted the Eastern Seaboard, pushing the Appalachian Mountains high into the sky—American Himalayas that would have buried the Peach State. The collision injected giant blobs of magma deep into the crust—perhaps some 10 miles or so belowground. But today that old magma offers a granite face to the sunlight here, everything else on top having been completely eroded away in the meantime. “That just blows my mind,” Holland said.

> Could we leave a time capsule for inhabitants of the next supercontinent to find 250 million years from now, just like we find fossils from Pangaea of 250 million years ago?

If we aspire to send a time capsule deep into the future, then Holland’s work is sobering. In one of his papers, a map of North America shows where sediments, and therefore fossils, have been preserved from across the entire 20-million-year-long Neogene period (23 million to 2.6 million years ago). Except for two tiny islands of preservation marooned in the middle of the continent and a fringing of old sediments along the coasts, it’s almost completely blank. “We have remnants of that sediment across the U.S.,” Holland says of the surviving islands of Neogene-age stuff in the middle of the country. “But even all those areas are uplifting,” or being pushed up by tectonic forces, and the unyielding work of erosion will most certainly plane them down. “So [the sediment is] a few tens of millions of years old, but it’s not going to last a whole lot longer.”

Making it into the very long-term fossil record requires getting buried by sediment, which, given enough time, becomes sedimentary rock. There are extraordinary quasi-exceptions to this rule: a rhino-shaped cave is etched into the basalts of the Pacific Northwest where an actual rhino was covered in lava 15 million years ago and left behind a cartoonish cavity of itself in the rock. But typically things don’t get preserved in lava. They get buried in stuff like muds, silts and clays, or they skip this step and make the rock themselves, as coral reefs do.

But burial isn’t nearly enough. For safe passage to the far future, you need to make sure you get interred in what’s called a sedimentary basin—a region that is sinking for larger, tectonic reasons, making space (“accommodation” in geology) that sediments can fill. A mastodon that gets buried in a swamp might last a few millennia in the dirt, but if that old sediment is part of a vast region that’s being subtly uplifted, then everything—and that means *everything*—will be lathed down to nothing by the forces of erosion.

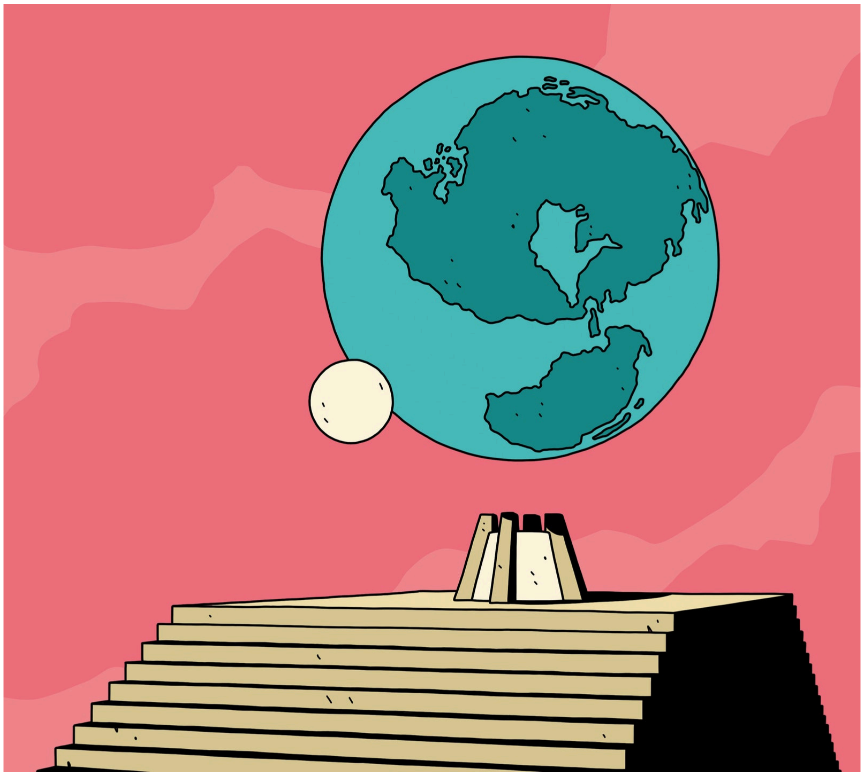
Examples of this relentless demolition abound. The late, great Ancestral Rocky Mountains once stood where the current range does—and with equal grandeur—but were long ago worn as flat as a billiard table. If solid mountains in the wrong place have no chance of making it into the deep future, what chance would the hollow glass-and-steel façades of a human city have, much less our time capsule?

In those rare places where the crust is actively sinking—in the sagging flanks adjacent to new mountain chains or in the drooping, stretched, taffylike crust where a continent is trying to tear itself in half—sediments will fill the space above the slumping crust. These regions are where the fossil record begins. Unfortunately, today only 16 percent of Earth’s land surface is constituted of such sedimentary basins.

“The other place people might think to put a time capsule is at the bottom of the ocean, on the abyssal plains, right?” Holland said.

They would be fools. Continental crust floats above the mantle essentially forever, but deep-ocean crust is far denser, so it gets continually fed to subduction zones at the edges of those ocean plates and destroyed. As a result, half the ocean floor is younger than 85 million years old. That sounds ancient, and it certainly is, but it's still young enough to have missed out on the first 80 percent or so of the age of animal life (and more than 98 percent of the full history of Earth). If we want to leave a time capsule, say, for inhabitants of the next supercontinent to find 250 million years from now, just like we find fossils from the Pangaea of 250 million years ago, then the ocean floor is a terrible repository. "The oldest oceanic lithosphere we have is 180 million years old, and the fate of most oceanic lithosphere is to get subducted," Holland said. "So if you put it down there, you're going to get it for only 200 million years. And we are in it for the long haul here."

Yet we do have a vast and vastly older fossil record of the oceans than any of the existing ocean crust on Earth today. Some of this rock is from pieces of deep ocean crust that occasionally got smudged onto the sides of the continents during collisions and outlived the rest of their plates. Far more commonly, though, it exists because the seas were draped high above the continental crust in the deep past, leaving a fossil record of ocean life in surprising places, like roadside outcrops in Kansas that spill shark teeth and the bones of giant seafaring reptiles. And in fact, we still have huge shallow seas sitting atop continental crust today. These waterlogged swaths of the continents are what's known as the continental shelves—gently sloping extensions of the land that slink below the waves at the shoreline and then far out to sea before finally diving into the abyss. If it's stupid to put our time capsule on the deep ocean floor, which gets continuously destroyed, what about these narrower perches just offshore?



A rough approximation of “Pangea Ultima” (250 million years in the future) based on maps by Christopher Scotese.
Federico Tramonte

“You do have a couple of things to contend with if you’re putting stuff on the continental shelf,” said Hannah Sophia Davies, a postdoctoral researcher of tectonics and sedimentary systems at the Free University of Berlin, who was similarly intrigued by my bizarre assignment and agreed to play along. The climate is always changing, you might have heard. What this has meant in practice over the past few million years, as the planet has plunged into and out of extraordinary ice ages, is that there are equally extraordinary changes in sea level—from more than 400 feet lower than today at the depths of the glacial periods to perhaps more than 20 feet higher than now during temporary millennia-long breaks from the cold, like the one we’re currently in. The brief memory of recorded human history may lull us into an expectation of stable shorelines, but the seas have in fact oscillated wildly throughout the past. And wherever they pause, they begin to chew away at the landscape.

“As the sea level changes, it progressively cuts into the land, so that might kind of erode the material away where you’re trying to preserve the time capsule," Davies said. This is a problem because the sea level is definitely going to change—first, perhaps, by rising dozens of feet in the geological short term as a result of human-caused warming. But eventually our carbon dioxide will be washed out of the system, and perhaps in 400,000 years we'll fall into a new deep ice age. If so, the sea level will drop hundreds of feet, the shelves will once again be exposed to the bracing air, and erosion will reign.

What if we put our time capsule a little deeper, near the edges of the shelves, which always stay below sea level but remain precariously perched above the ocean crust? "I would think that's not a particularly good idea," Davies said, "because every now and again you have these massive submarine landslides called turbidity currents, and those transport all the material offshore into the deep ocean. So they will probably just destroy anything that you put there."

Even worse, the Atlantic continental shelf and other so-called passive margins, which just sit there placidly collecting sediment, unmolested by tectonics, don't stay passive forever. In 1755 a preposterously giant earthquake leveled Lisbon, killing tens of thousands of pious churchgoers—on All Saints' Day, no less. The magnitude 8.7 tremor was awful enough that in the minds of some Enlightenment-era philosophers, it destroyed the idea of an all-powerful, kind and loving God. It might have also kick-started the destruction of the entire Atlantic Ocean. The event might have been the initial grumblings of a new subduction zone, a tectonic maw that will someday invade the Atlantic Ocean through the Strait of Gibraltar, chewing up ocean crust as it spreads. If so, it would only mirror its more mature counterparts across the Atlantic today: two crescents of deep ocean trench where the seafloor is similarly being fed to the mantle. For their part, these American subduction zones may infect the rest of the western Atlantic, effectively throwing into reverse a tectonic spreading system that has been successfully pushing the ocean apart for 180 million years. Ultimately, this action may swallow the entire Atlantic as the planet inaugurates its next supercontinent. Needless to say, this would probably be bad for the fragile sediments of today's Atlantic continental shelf.

> Every message needs a receiver, even if it's just to puzzle over some baffling zircons hundreds of millions of years from now.

Elsewhere the immense submerged swath of shelf from Australia to Vietnam, which hosted countless stegodonts and, later, humans in the ice ages—and which now hosts their fossils deep underwater—is similarly slated for destruction. "Australia is going to collide with Southeast Asia, which will generate a huge mountain chain," Davies said. "And that happens super quick, in, like, the next 30 million years."

Returning to land, what about that 16 percent of continental crust that is home to sedimentary basins? Well, most of it is desert, which brings us to the next hurdle: taphonomy, or the process of fossilization itself. If one is extraordinarily lucky, the cliff walls of Navajo sandstone will occasionally reveal to them the permineralized bones of a hapless prosauropod, killed by a sand dune collapse in the Jurassic, but never in much detail. "Sand is really porous, so sandstones don't preserve fine detail," Holland said. "So, yeah, that would not be my favorite place to put something."

By this point in my search, having eliminated most of the world, I was stumped. I'd learned that we want to put our capsule in a sedimentary basin, hermetically sealed off from the oxidative ravages of the surface world, but probably not in a desert and not in—or perhaps even near—the ocean. Looking at Holland's map, I thought I had a breakthrough: bury it at the bottom of the Black Sea! After all, it's in a sedimentary basin in the middle of a landmass, and it's clearly anoxic—it even pickled the shipwrecks of Roman galleys in breathtaking detail. Nope. "That whole area—basically, as you go from the Himalayas through the Middle East, up through Turkey and into the Alps—is just a fright zone," Holland said about the impossibly complex and ongoing crashing of Eurasia into Africa. "There's so much collision that I think that whole area has really poor preservation potential. Like, the Mediterranean is going to be gone."

Okay, fine. Where are we going to put this thing?

"I like the East African rift," Holland said. "I would probably put it there."

Some 200 million years ago, when the planet decided to break up Pangaea, the first attempts at tearing North America from Africa failed, leaving behind a necklace of deep, narrow rift-valley lakes from Massachusetts to South Carolina. Something similar may be underway now in East Africa, home to Lake Malawi and Lake Tanganyika. The ancient beds in North America still give up scaled fish fossils and lakeside crocodilian footprints as they erode from outcrops at the edges of parking lots in Newark or quarries just outside Washington Dulles International Airport. With this in mind, then, perhaps we should charter a pirogue out to the middle of Lake Malawi, drop our time capsule into its deepest, most anoxic waters, cross our fingers and hope for the best. Or maybe there's something we can do to help the preservation process along.

We've avoided discussing so far what this thing should be made of. A metal canister might do for a couple of decades, but we need to be more selective as we reach deeper into the geological future. Metal corrodes; glass devitrifies. Even our infamous legacy of plastics won't last long in the geological record: it will degrade into a strange residue of long-chain organic biomarkers. "Chemical weathering is the real killer," Holland said. And chiseling something out of granite would be downright idiotic because the weathering and erosion of silicate rock such as granite is just about the most reliable thing that happens on our planet. "Minerals can be ranked in terms of their susceptibility to chemical weathering," he said. “Something made of quartz is extremely resistant. And actually—I’m not sure how you get as much of it, but the most resistant thing I can think of is zircon.”

We still have nearly indestructible grains of zircon from the very dawn of Earth’s history, almost 4.4 billion years ago, even though nothing else has survived from the primeval world of the early Hadean eon. “We have zircons that are basically as old as Earth, right?” Holland said. “So if you could, if you wanted to make something that was going to basically last forever, I’d make it out of zircon.”

> It’s no small irony that the very reason this exercise is near impossible is the reason we’re here in the first place.

When I described Holland’s East African rift idea to Davies, she was wary (fearing the capsule might meet an early grave at the bottom of a new East African Ocean), but the wheels began turning when I mentioned Holland’s zircon plan. “Oh, yeah, that’s good. You could, like, laser etch in zircon.... It would even stand a chance of surviving orogeny,” she said, referring to the titanic mountain-building collisions that mangle and cook lesser minerals. “So actually that’s an interesting discussion, then, because you don’t really need to find it in an outcrop. You could find it detritally.” In other words, you wouldn’t have to uncover the time capsule in the rocks where it was originally placed, which may erode away; instead you could find it wherever it ended up.

“If it eroded down a mountain and you dug it up at the coast before it got to the continental shelf or if it ended up buried in the ocean, maybe that would work,” Davies said, adding that it could be possible to build a zircon with a strange, unnatural isotope concentration that would signal its human-made origin. “If you’re just kind of screaming into the void, ‘We were here,’ then it would maybe make sense to distribute a lot of these weird zircons just to mess with future civilizations. But then, I guess, it depends on what the point of the time capsule is: Are you making a Voyager disc? Are you saying, ‘Here’s humanity. Here’s what we were’?”

This question leads to the final and perhaps most speculative part of an exercise that has long since veered into irresponsible speculation: someone has to find the damn thing. Every message needs a receiver, even if it’s just to puzzle over some baffling zircons hundreds of millions of years from now. This requirement probably eliminates the most obvious solution to all of the problems outlined so far: Simply find the most stable, interior part of a continent, far from any tectonic drama. Drill a mile-deep hole, put your time capsule in there, and seal it up with whatever—cement, maybe. And indeed, this approach would almost certainly work. There’s just one problem. “You can put the time capsule in a deep borehole in the middle of the planet and seal it up, but nobody’s ever going to find it,” Holland said.

To ensure our laser-etched, isotopically deranged block of zircon gets discovered in the future, it’s not enough for it to be committed for safekeeping in a subsiding sedimentary basin or even dropped into some fathomless shaft in the bedrock. After all, there are miles-thick stacks of strata positively loaded with fossils underneath our feet that no one will ever study because they’ll never see the light of day. To actually transmit our message, then, our rocks have to be subsequently uplifted at some point hundreds of millions of years from now just enough to be eroded and revealed at the surface. But then you’d have to be there at the exact right time to catch them before they’re inevitably eroded out of existence. And the prospect of being at the right place at the right time—in the window of a few decades or so—to look for this thing when it’s exposed on the surface somewhere in our several-hundred-million-year journey ... well, this is all getting a little silly.

Our knowledge of the far future of plate tectonics peters out somewhere around 250 million years from now, and even then it’s an understatement to call our grasp of this future geography sketchy. Nevertheless, every 400 million to 600 million years, it seems, all the continents tend to assemble into one hemisphere-spanning union called a supercontinent, with Pangaea being the most recent example. By applying what they know about plate tectonics and subduction zones and running a model forward as far as is reasonable (and then quite a bit further), several groups of geoscientists have tried their hand at projecting the next supercontinent's configuration some 200 million to 250 million years in the future. Three of the groups predict that a behemoth will be huddled around the tropics (although the fact that one group has it forming over the North Pole gives some indication as to the level of guesswork involved). The canonical version, called Pangaea Ultima, was imagined by Northwestern University geologist Christopher Scotese.

Pangaea Ultima is virtually a reprise of the previous Pangaea: the Atlantic Ocean ultimately closes much in the manner described earlier, with the Americas and Africa reversing course and lazily drifting back toward each other before slowly, if violently, reuniting 250 million years from now. In this scenario, Davies had her eye on Namibia.

Namibia is a sedimentary standout today. And it's unlikely to be disturbed by any major tectonic disruptions in the very long haul—until that happy day when it crashes into the Americas and gets uplifted as part of a lengthy mountain chain trending east-west at the very heart of the supercontinent, not unlike the Central Pangaean Mountains hundreds of millions of years before them.

Discouragingly, even if paleontologists exist in the world of Pangaea Ultima 250 million years from now, and even if we luck out on everything outlined so far, the rocks to which we entrust our capsule would have to end up on a part of the planet that these future paleontologists would be likely to study. It might seem like a strange quibble, but today our understanding of the history of life on Earth is hugely biased toward the fossil record of the Northern

Hemisphere for very human reasons, up to and including the history of global economic development. And although speculating on the political economy of the next supercontinent might be even more ridiculous than musing about its tectonics, there are reasons to worry about the prospects of anyone—no matter where they come from on the tree of life—ever carrying out fieldwork across enormous swaths of Pangaea Ultima. That's because except for its polar fringes, it will be an absolute hellhole.

Supercontinents are miserable places to begin with. The last Pangaea, for instance, featured an expansive, arid equatorial interior that was virtually devoid of life, brutally hot and streaked in toxic, superacidic salt playas. The interior of the next supercontinent is likely to be even worse because the sun will grow about 2.5 percent brighter by the age of Pangaea Ultima.

Paleoclimatologist Alexander Farnsworth of the University of Bristol in England and his colleagues have produced a menacing picture of the climate of this world. Daily temperatures could exceed an unthinkable 122 to 140 degrees Fahrenheit for months on end across the entire supercontinent. Mammals can't survive sustained temperatures above 104 degrees F—a seemingly hard limit over our entire quarter-billion-year evolutionary history—and the components of photosynthesis break down at 104 to 140 degrees F. Unless future paleontologists restrict themselves to the polar fringes of Pangaea Ultima, they will die. "If the time capsule survives the continental collision, then maybe it would be exposed in your Central Pangaea Ultima Mountains," Davies said. "But then, yeah, there's the problem of getting at it when it's 140 degrees out."

Where does that leave us? If nothing else, this ridiculous thought experiment should drive home what a churning, restless planet we live on. This exercise would be trivially easy on Mars or the moon because those are dead, hopeless worlds. It's not difficult on Mars to find river and lake sediments from four billion years ago exposed on the surface today. The moon still bears the fresh wounds of an asteroid impact 4.3 billion years ago. On Earth there aren't even chunks of rock that old, and the Chicxulub crater, the biggest impact crater known to have formed in the past billion years, is hardly visible on the planet's surface, buried under tens of millions of years' worth of limestone and covered in jungle. If there were bigger impacts over that immense time span than the one that wiped out the dinosaurs, they've been all but erased.

That's because our planet is alive. Plate tectonics ceaselessly reworks Earth's surface: it pushes up mountains and creates and destroys oceans. Weather wears those same mountains down, and rivers carve canyons, seeding the oceans with nutrients that slough off the land and fuel life. This patient demolition helpfully draws CO_2 out of the air as well, maintaining a habitable temperature for complex life through the chemical alchemy of rock weathering and erosion, which transforms carbon in the air to limestone at the bottom of the ocean over hundreds of millennia. This sequestration of CO_2 is almost perfectly in balance with its contribution to the atmosphere elsewhere as it vents from volcanoes—volcanoes fired by subduction, rifting and all the other processes that ceaselessly remake our surface world. It's a good deal for life on Earth. And it's no small irony that the very reason this exercise is nearly impossible is the reason we're here in the first place.

"I think it's becoming more and more obvious to a lot of geologists that plate tectonics is necessary for the long-term habitability of a planet," Davies said, considering the strange thought experiment I had recruited her into. "It's almost an interesting kind of catch-22: you need plate tectonics to develop civilizations, but plate tectonics can quite easily just destroy any remnants of civilization on a planet."

Peter Brannen is a science journalist based in Cambridge, Mass. His latest book is *The Story of CO_2 Is the Story of Everything* (Ecco, 2025).

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Animals

- ## These birds learned to tweet like R2-D2. Listen to the uncanny results
  This lovable Star Wars droid is helping to shed light on why some bird species are better at mimicking sounds than others
- ## Spiders build giant decoys to scare predators from webs
  Spiders scare off predators by seemingly supersizing themselves
- ## Zoo lunch mishap reveals lizards’ hidden fire detector
  Australian “sleepy” lizards are not so sleepy when it comes to fire
- ## How woodpeckers turn their entire bodies into pecking machines
  These birds’ drilling approach is more like extreme tennis playing than weight lifting

These birds learned to tweet like R2-D2. Listen to the uncanny results

This lovable Star Wars droid is helping to shed light on why some bird species are better at mimicking sounds than others

By Kate Graham-Shaw edited by Andrea Thompson & Sarah Lewin Frasier

Thomas Fuchs

A long time ago in a galaxy far, far away, R2-D2 beeped and booped—and now birds that copy the *Star Wars* character are giving scientists fresh insight into how different species imitate complex sounds. A recent study in *Scientific Reports* analyzed the vocalizations of European Starlings and nine species of parrots, including budgies, to see how accurately each bird can mimic R2-D2's robotic whirring.

Researchers analyzed recordings they found online of birds imitating the plucky droid to find out how statistically similar each bird's noises were to a model of R2-D2's sounds. The starlings, a type of songbird, emerged as star vocalists: their ability to produce "multiphonic" noises—in this case, two different notes or tones expressed simultaneously—allowed them to replicate R2-D2's complex chirps the most accurately. Budgies and other parrots, which produce only "monophonic" (single-tone) noises, copied the droid's sounds with less accuracy and musicality.

The differing abilities stem from physical variations in the birds' syrinx, a vocal organ that sits at the base of the avian windpipe. "Starlings can produce two sounds at once because they control both sides of the syrinx independently," says study co-author Nick Dam, an evolutionary biologist at Leiden University in the Netherlands. "Parrots are physically incapable of producing two tones simultaneously."

It isn't known exactly why species developed differing control over their syrinx. "Most likely some ancestor of songbirds happened to evolve the ability to control the muscles on both sides of the syrinx, and this helped them in some way," says University of Northern Colorado biologist Lauryn Benedict, who wasn't involved in the study. A leading explanation involves mating: the better a male songbird sings, the more females he attracts.

Some birds such as starlings (*right*) are better at mimicking R2-D2 (*left*) than others.
Jay L. Clendenin/Los Angeles Times via Getty Images (*left*); Gary Chalker/Getty Images (*right*)

Although the study is "a really elegant way of approaching this question of whether the starlings versus the parrots are capable of producing the same sound with the same accuracy,” it doesn’t fully address how much training or reward the birds received, says Nicole Creanza, an evolutionary biologist at Vanderbilt University, who also wasn’t involved with the research.

Benedict agrees that the researchers could work with bird owners to do tightly controlled trials. (And she and other scientists, including some of the study authors, are looking for public submissions of other examples of parrots imitating sounds for their Many Parrots Project.) “A wider sample would be really neat,” she says, “and they could test all kinds of different sounds, not just R2-D2!”

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https://www.scientificamerican.com/article/these-birds-learned-to-tweet-like-r2-d2-listen-to-the-uncanny-results

These spiders weave themselves giant doppelgängers to scare away predators

Spiders scare off predators by seemingly supersizing themselves

By Gennaro Tomma edited by Sarah Lewin Frasier

This spiderweb structure presents the illusion of an intimidating bigger spider.
Richard Kirby

What's scarier than a spider? A really big spider, of course. A newfound defensive tactic takes advantage of this idea: researchers documented spiders building giant spiderlike silhouettes on their webs to ward off predators.

These decoys are an example of "web decorations" that some spiders are known to produce, often to prevent getting eaten, avoid bird strikes or attract prey. Such ornaments come in many shapes and sizes, but this is the first time scientists have documented spider-shaped decor.

From 2012 to 2022 a research team collected observations of these unusual webs in Peru, the Philippines and Madagascar, focusing on about 300 individuals from the genus *Cyclosa* that are typically only a few millimeters long. The researchers published their findings in *Ecology and Evolution*.

The spider doppelgängers are made of prey carcasses, plant debris, and other organic materials. They have a central structure from which “legs” branch out. The team proposes that the constructions serve primarily as a defense from predators such as hummingbirds or helicopter damselflies. But different species might use them in different ways.

In Peru, the spiders seem to use the decoys “as puppets,” says study co-author Phillip Torres, an entomologist and television host. “They will be on the top of the figure, and they shake the web, so they are pretending to be a bigger spider.” Small predators might be scared by a larger spider, and predators that specialize in eating the real, smaller arachnid might want to avoid a supersized one. In the Philippines, the spiders seem to instead hide inside the structure and wait for the predator to go away.

Dinesh Rao, an ecologist at Veracruzana University in Mexico, who wasn’t involved in the study, emphasizes that figuring out the constructions’ precise function requires more research: “You need either careful observations or experimental conditions where you actually look at how [predators] respond to these structures.”

Gennaro Tomma is a freelance journalist who covers science, with a focus on the natural world, biodiversity, conservation, climate change, environmental and science-related policies, and more. His work has appeared in the *New York Times*, *Science*, *National Geographic*, *New Scientist* and other outlets. Find more on his website: https://gennarotomma.it

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https://www.scientificamerican.com/article/spiders-build-giant-decoys-to-scare-predators-from-webs

Zoo lunch mishap reveals lizards' hidden fire detector

Australian "sleepy" lizards are not so sleepy when it comes to fire

By Clarissa Brincat edited by Sarah Lewin Frasier

The smell of smoke activates this otherwise "sleepy" lizard *Tiliqua rugosa*, also known as the shingleback skink or bobtail lizard.
Totajla/Getty Images

A burned lunch at the Audubon Zoo in New Orleans did more than just disappoint a hungry staffer. As soon as a smoke plume from the mishap drifted into their enclosure, Australian "sleepy lizards," a type of skink, suddenly stopped whatever they were doing—they tensed, flicked their tongues, and began pacing their enclosure's edges and digging in the substrate, frantic to escape. Other reptile species in the same room didn't flinch.

The incident sparked a scientific hunch: perhaps the lizards, which happen to hail from particularly fire-prone regions, had evolved to recognize a blaze's chemical cues.

To test this hypothesis, Chris Jolly, a conservation biologist at Macquarie University and Charles Darwin University, both in Australia, and his colleagues exposed 10 adult female sleepy lizards to individual puffs of smoke and water vapor and separately to recordings of crackling wildfires and white noise. The lizards fled in response to smoke but were unfazed by water vapor or either recording. The findings, published in *Biology Letters*, suggest these lizards rely on smell—not hearing—to detect fire at long range, unlike some other lizards, frogs and bats.

This idea aligns with Australian sleepy lizards' known use of scent to recognize partners, with whom they form lifelong pair-bonds, as well as to find food and detect predators. "Smoke also tends to travel ahead of the flames and cuts through background noise," Jolly says, "making smell a more reliable early warning than sound in open, windy, noisy environments."

Many of the lizards tested had probably never experienced wildfire; their capture site hadn't burned in more than 50 years. Yet they still bolted when they sensed smoke, suggesting an innate adaptation. (The strong response was notable given the animals' typical slow, deliberate movements, which Jolly assumes inspired the "sleepy lizard" moniker: "They're rarely in a rush to do anything, except, apparently, to escape from fire!")

Juli Pausas, a research scientist at the Spanish National Research Council, who was not involved in the study, says that although the sleepy lizards' reaction to smoke could indeed represent adaptation to fire—something also seen in certain bats, possums and lizards—future studies will have to rule out other explanations such as a general aversion to toxic substances in smoke.

"Nevertheless, the paper contributes to the emerging recognition that certain animal behaviors may represent fire adaptations, a topic that has been underexplored until recently," Pausas says. As fires intensify amid climate change, the paper's authors say, these sensory skills could mean the difference between survival and death.

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How woodpeckers turn their entire bodies into pecking machines

These birds' drilling approach is more like extreme tennis playing than weight lifting

By Rohini Subrahmanyam edited by Sarah Lewin Frasier

Tapping woodpeckers harness their muscles more like tennis players than like weight lifters.
Diana Robinson Photography/Getty Images

Woodpeckers operate at an extreme level, boring through solid wood with forces more than 30 times their own weight and drilling up to 13 times a second. How do they never miss a beat while head banging so hard?

It turns out that the birds tense up their entire body to smash through wood, letting out short, explosive grunts with each strike, report Brown University biologist Nicholas Antonson and his colleagues in the *Journal of Experimental Biology*. "Woodpeckers really are nature's hammer in a sense," Antonson says.

To study how the birds tap, the researchers first humanely captured eight wild Downy Woodpeckers and carefully inserted electrodes into their muscles in the laboratory. The electrodes fed into a tiny, fitted backpack that recorded electrical signals from contracting muscles as the birds pecked. They also checked whether the woodpeckers held their breath during exertion (like weight lifters tend to do) or exhaled (like tennis players) while striking the wood by examining airflow through the birds' air sacs—small, balloonlike structures that help them breathe in and out. By matching these measurements with high-speed videos, the scientists tracked the woodpeckers' taps down to every four milliseconds.

Instead of using a single muscle to control the action, woodpeckers activated "every muscle from the head to the tail," Antonson says. The birds used their powerful hip flexors to push forward, clenched their tail and abs to prepare for the strike, and stiffened the back of their head and neck on contact—similar to the way you might stiffen the back of your wrist when you hammer a nail. They then engaged a different set of hip and neck muscles to draw back.

The birds also perfectly paired their pecks with sharp exhalations "as another means of stabilizing their core muscles and powering through those strikes," Antonson explains. "To be able to breathe out 13 times per second and inhale on the order of 40 milliseconds is really impressive." Songbirds, which aren't closely related to woodpeckers, are the only other birds known to so precisely time their breaths, which they do as they sing.

"Pecking is a full-body exercise," says University of Alabama biologist Nicole Ackermans, who studies brain damage in woodpeckers and head-butting sheep. Coordinating "micro breaths" with muscle clenching and creating "this hammerlike structure in their whole body is such a unique approach," she adds.

Rohini Subrahmanyam is a biologist turned science journalist. She loves writing about interesting creatures on our planet. Subrahmanyam received a Ph.D. from the National Center for Biological Sciences at the Tata Institute of Fundamental Research in India. Follow her on X (formerly Twitter) @rohsubb and on LinkedIn, and see her portfolio here.

https://www.scientificamerican.com/article/how-woodpeckers-turn-their-entire-bodies-into-pecking-machines

Archaeology

- **History smelled. Here's how we're sniffing it out**
  How can reconstructing long-lost smells of ancient artifacts help us connect with the past?

Ancient incense, cosmetics and mummies: Scientists sniff out the scents of the past

How can reconstructing long-lost smells of ancient artifacts help us connect with the past?

By Gayoung Lee edited by Andrea Thompson & Clara Moskowitz

Shideh Ghandeharizadeh

What's the first thing you notice when you step into a museum? Is it the long-faded colors of ancient artifacts from all around the world or the hushed sounds of visitors discussing what they see? Maybe there's a replica of scratchy old fabric you can touch. Some locations might even offer an edible treat inspired by an ancient recipe. Museums allow us to indirectly experience the past by tapping into our primary senses—sight, hearing, taste, touch—but more often than not, smell is missing.

Representations of the past are often odorless. But smell probably played a huge role in many historical realities, says Barbara Huber, an archaeochemist at the Max Planck Institute of Geoanthropology in Germany. The conspicuous absence of scent in our study of history (not counting the musty tang of many museums) has inspired Huber and a growing community of chemists and archaeologists to track down some molecular remnants that can let us smell the past. For example, she created Scent of the Afterlife, a mix of aromas that captures the range of smells that would have accompanied mummification processes in ancient Egypt. Some of the recent advances in the quest to catch a whiff of history are featured in a new collection co-edited by Huber, *Scents of Arabia: Interdisciplinary Approaches to Ancient Olfactory Worlds* (Archaeopress, 2025).

READ MORE: What Sniffing Mummies Taught Scientists about an Ancient Society

Scientific American spoke to Huber about the "science of smell" and its significance to our understanding of lives long gone.

An edited transcript of the interview follows.

We know smell is linked to very specific areas of the brain. What are these areas, and why does that link make olfactory interactions so important throughout history?

The sense of smell is very much connected to the parts of our brain that process emotion and memory. There's also a very direct link from our olfactory bulb in the nose to the amygdala and the hippocampus in the brain, so we actually react to something we smell before we even think about it. And this process comes from a very long evolutionary tradition. Our ancestors needed this ability to memorize specific smells because they alerted them to danger.

We do not think nowadays about the major effect scent has on how we perceive and navigate the world. And it has a huge effect on our well-being—an interesting fact that COVID reminded us of, because people relearned how important the sense of smell was when they lost it.

Analyzing remnants from incense burning can help shed more light on how people along the incense road (a trade network covering a broad area from the Arabian Peninsula to the Mediterranean) used the materials they burned.
Chris Leipold

We don’t really think about smell when studying the past. One of the problems is that, from a methodological point of view, it is incredibly hard to study. The scents and smells and stenches—whatever was there in the past—were already gone before archaeologists could come and investigate the sites. New chemical and biomolecular methods in archaeology have kind of reopened the door to continue to study these things. And of course, what we have from ancient texts can also help a lot.

When we do find all these details, they can enrich our understanding of many aspects of past ways of life, from medicine to perfumery and cosmetics to trade, as well as things such as identity or social status. There were wars over spices—these tiny powders and resins had such a strong effect on people that they went to war for them!

It’s fascinating to me that smell is tangible and intangible. How has studying something with that kind of duality changed your perspective on doing research?

The interesting thing is that these molecules that we detect, or that we are still able to detect, can tell us a lot about ancient materials.

At the same time, when we reconstruct and re-create them like we did with Scent of the Afterlife, we can bring a piece of the past to visitors today. And that's not just an object that has been found and excavated and then displayed in a museum. In a scent exhibit, people can actually perceive it. This way of perception is a kind of participation in the past. If you enter a room and can somehow smell how it must have smelled in a mummification room in ancient Egypt—and you see all the raw materials and everything—you're being immersed in a different way in history and in learning.

Studies have shown that this multisensory way of learning—especially when it involves smell—can enhance how you think about specific things and enhance learning effects. I think that's because it's so connected to emotions. When you are at an exhibition, you might recollect memories when you smell something that is very tied to you. It connects us more deeply to earlier ways of life.

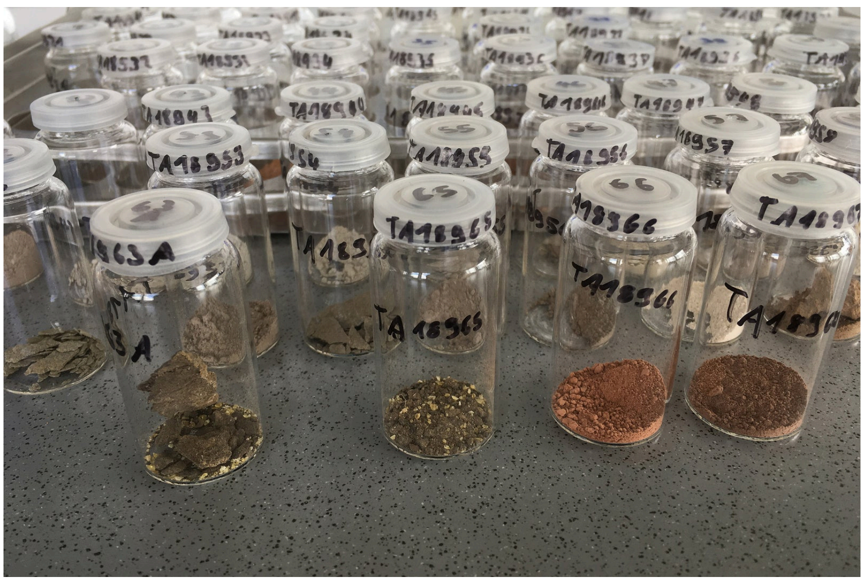
I was just thinking back to Scent of the Afterlife, the perfume you reconstructed from ancient Egyptian mummies, and the way everyone at *SciAm* reacted to the sample we had. We each remembered specific experiences from our own lives—for example, I said it smelled like a very well-managed "grandpa car."

[Laughs.] That's brilliant.

I'd love to hear more about the nitty-gritty science involved in the kind of analysis needed to re-create such smells.

We work with organic materials. Sometimes the original substance is not even there anymore—but we look for what we call scent archives. These are specific objects—a perfume flask or a cosmetic container or an incense burner—related to the kind of practices or actions that require scented materials. Say you have a scented cream, and there are remains of it, a crust or something like that, in your pot. Then we can take tiny samples and do an analysis on them. We first identify all the different compounds of the sample with gas chromatography to separate the various molecules in it, then we analyze it with mass spectrometry [an analytic method that identifies an unknown chemical compound based on its spectral behavior]. Then, basically, we're able to identify every single compound.

It gives us clues about trade, for instance. We find all the different ingredients and look at whether these ingredients are local—Can people just go out there and harvest them? Or do they need to import them from distant lands?



Glass vials hold samples of ancient incense burners for chemical testing.
Barbara Huber

How does decomposition affect the process? From what I understand, the compound you detected might not have been the original compound.

Let's take, say, vanillin, a molecule that has a vanillalike scent. When we find vanillin, someone might jump to a conclusion and say, "Oh, we have vanilla! Oh, cool! They used vanilla in the past!" But vanillin is also a decomposition product of a larger molecule called lignin, a common component of woody tissue. So a lot of wood things have this vanillin compound when they break down.

Thus, when you find it, you need to be very careful because there isn't always only one possibility for where it came from. We do a lot of detective work on our side to analyze what we have and try to make sense of it.

The introduction to your book says it "challenges traditional trade-focused narratives." What does that mean?

Regarding ancient materials—especially aromatic materials in Arabia—the study of trade and the incense road [a network covering a broad area from the Arabian Peninsula to the Mediterranean and dealing mostly with the circulation of incense] was always an interesting point for researchers. But the problem is that the incense road was very often looked at from the perspective of classical scholars—so, texts from ancient Greece or Rome. From the very start, the story of the incense road was told by outsiders who were also not really contemporary. We don't have any evidence from the earlier periods, the Iron Age and the Bronze Age, in ancient Arabia. So for us, it was most interesting to look at evidence other than ancient texts that can tell us a little bit more about the trade of aromatics.

Examples of ancient incense burners from the Oasis of Tayma in what is now Saudi Arabia. M. Cusin/Orient Department, German Archaeological Institute/"Incense Burners at the Oasis of Tayma, Northwest Arabia: An Olfactory Perspective," by Barbara Huber, in *Polish Archaeology in the Mediterranean*, Vol. 29, No. 1; December 30, 2020 (*CC BY 3.0 PL*)

Is there a particular chapter or case study that comes to mind when you think about the overall framework or objectives of the anthology?

In one case study, we looked at the content of incense burners and found a plant in the genus *Peganum*. Its common name is Syrian rue, and it's a medicinal and psychoactive plant. We realized that in these incense burners specifically, people used it for therapeutic or psychoactive purposes. This finding was very interesting because it means the practice of incense burning seems to not only be sensorial but also have this medicinal component.

The close study of these incense burners revealed something we'd had absolutely no idea about: medicinal practices in Arabia before the Islamic period. We all of a sudden had an idea of how people used their local pharmacopoeia [their collection of available medicinal ingredients] for treating illnesses; in this case, they burned the substance and then probably inhaled the smoke, rather than just applying it to the skin or drinking it as an infusion.

The practice of burning incense, which is very linked to Arabia—there is the incense road and emblematic scents such as frankincense and myrrh—left a legacy that is still alive today. Although it's part of people's lives today, it goes all the way back. In the book, we basically follow it to the roots of where it began, how it shaped societies and the identity of a particular part of the world—and, of course, how it remains connected.

For me, the collection reminds me that history isn't something we only see.

Gayoung Lee is a science journalist and former news intern and Games ace at *Scientific American*. A philosopher turned journalist, originally from South Korea, Lee is interested finding unexpected connections between life and different science, particularly in theoretical physics and mathematics. You can read more about her here: https://gayoung-lee.carrd.co

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https://www.scientificamerican.com/article/how-archaeology-is-reviving-the-smell-of-history

Artificial Intelligence

- **How one mom used vibe coding to build an AI tutor for her dyslexic son**
  Faced with her son’s struggle with dyslexia, one mom built an AI platform to help kids learn their own way

How one mom built an AI tutor for her dyslexic son

Faced with her son's struggle with dyslexia, one mom built an AI platform to help kids learn their own way

By Deni Ellis Béchard edited by Clara Moskowitz & Seth Fletcher

Martin Gee

A dyslexia diagnosis was supposed to offer solutions for a boy named Tobey. It was first identified in a routine school screening, which led to tutors, speech therapy, a neuropsychological evaluation and a spot at a Manhattan school that could better suit his needs. But Tobey continued to struggle. One winter afternoon in early 2025, at age 11, he came home discouraged, says his mother, Arlyn Gajilan. Why, he asked, did she keep telling him he was smart? "'I'm slower than everybody else. Why is it so hard for me?'" she recalls him asking. "That was like a gut punch," Gajilan says.

Gajilan, who has worked at Reuters for more than 14 years and was then digital news director, had been reading about artificial intelligence and custom generative pretrained transformers, or GPTs—tailored AI models that users can configure for specific tasks. After determining her data would be private, she fed one of the models Tobey's report cards, neuropsychological evaluations and individualized education programs for his dyslexia. She also gave it his interests: dragons from the book series Wings of Fire, battles with Nerf guns, a song or two from *Hamilton*. She told the GPT he was bright and competitive but found reading and writing difficult, and she asked it to look for the best pedagogical approaches. "You are a special education teacher with expertise in teaching kids with dyslexia," Gajilan recalls writing. "Your job is to help my son." Then she handed Tobey her smartphone.

The decision wasn't made lightly. Although Gajilan worked in technology, she didn't let Tobey use social media, and he didn't have his own smartphone. "I'm very conscious of the harm that technology can do," she says.

But the GPT provided a creative approach that surprised her. It helped Tobey organize paragraph structure, topic sentences and syntax in exercises that it turned into games related to his interests. "My kid is a little sassy," Gajilan says, "and the AI was giving back as much sass as he was giving. It would respond with things like 'Game on' or 'Is that the best you've got?'" After every session, she would tweak the GPT, telling it to increase the difficulty or asking it to explain how a recent lesson was pedagogically sound. Her experience is just one example of the growing use of AI in educational tech—especially to create bespoke learning tools designed for the needs of individual students.

Vibe Coding a Solution

When Tobey first began using the GPT, he was skeptical. "I was like, 'Could this really help me?'" he says. "But I was wrong. I can speak way more fluently and read more fluently, and I'm more confident with my math skills. I'm not doubting myself like I did before." Gajilan checked in with Tobey's teacher, Jacinta Capelli, who had noticed improvement over the course of several months. "Tobey demonstrated a notable increase in confidence," Capelli recalls, although she couldn't be sure AI was the cause.

Encouraged, Gajilan began considering how she could make the GPT available to her son's friends. She'd been a journalist her entire adult life, covering tech and start-ups, and she had helped redesign the Reuters website and rebuild its app. "It wasn't like I was coming at this purely from a Luddite space," she says. "I knew what product requirements were, but I don't know how to code."

> "This change to using AI is as profound, if not more profound, as when the Internet took over." —Arlyn Gajilan

"Vibe coding"—using AI language models to write code—was increasingly in the news when Gajilan was thinking about how to develop an educational platform, and research suggests that it has quickly moved from novelty to norm. A 2025 study from software company JetBrains reported that 85 percent of developers regularly use AI tools, and 62 percent rely on at least one coding assistant, AI agent or code editor. Instead of coding manually, vibe coders write what they want the AI to build in the same way that they might send a Slack message to an employee. The AI translates this text into code, providing iterations until users have the results they want.

Gajilan began experimenting with different software. She'd made the custom teaching GPT in February, and during spring break, sitting at the kitchen table, she trained herself in the use of vibe-coding tools. She aimed to build her own platform based on principles drawn from 450 publicly available papers on learning differences, from dyslexia to attention deficit hyperactivity disorder. She designed a user dashboard and a questionnaire that asked new students about their motivations and struggles. This setup allowed the AI to build a learning profile with goals and a lesson plan that it could adapt depending on how users responded. By mid-June she had launched the beta version, and by July she had a dozen subscribers paying $29 a month, logging 30-minute sessions a few times a week.

During this process, Gajilan filed two patents for an algorithm she developed to recognize when users are becoming frustrated. “It looks at a variety of things: when a kid’s accuracy drops off, when it takes longer for them to respond and when they’re using key phrases like ‘I don’t know’ or ‘This is too hard,’” she says. When the system detects a combination of those factors, it creates wellness breaks, guiding the user through movements such as jumping jacks or mindfulness exercises. Gajilan also gamified the platform, which she and her son named Tobey’s Tutor. Tobey’s drawings helped to inspire the designs of badges that kids can earn for completing different levels.

Parents can log into the dashboard and see what their child is working on, the lesson plan and its rationale. The lessons are original; nothing is off-the-shelf or reused. There are no worksheets, just exercises made to fit a particular brain. Gajilan added guardrails, too: if a child types words that hint at self-harm, the platform alerts a parent.

AI in Education

As AI systems become more sophisticated, a growing body of research is finding they can be effective for learning. A 2023 study that was not peer-reviewed showed an increase in scores on a state math test among seventh-grade students in North Carolina who had used an AI educational tool, with some of the benefit still visible a year later. A large 2025 review of classroom trials also found that using AI often boosted learning.

Scott Gaynor, head of the Stephen Gaynor School, the Manhattan private school that Tobey attends, has followed the development of both AI in general and Gajilan's platform, and he believes such a program could also help students who lack motivation for learning. For instance, low scores on standardized tests in the U.S.—only 22 percent of 12th graders achieved proficiency levels in math in 2024—have been attributed to many factors, from pandemic-related learning loss to widespread math anxiety to a general lack of interest.

Martin Gee

"This is where AI—and a program like Tobey's Tutor—comes in: it can create high-interest, tailored questions for that student," Gaynor says. "For example, [the hypothetical child I had in mind when I tried out the platform] was interested in tennis. I got a series of math word problems around tennis. There's no way a teacher in a public school with 30 students could come up with 30 different worksheets with 10 word problems on them for each child's interest. But once a program like Tobey's Tutor gets to know the children, it will create word problems around anything you want. Right away you've engaged the student."

Tobey says he likes how the AI makes exercises he hasn't seen before. "When you strip all the Wings of Fire stuff away, you just have a boring math problem or a reading essay. But then it incorporates [my interests] in a way where you know you're still learning something, but it makes it more fun."

Tobey's Tutor arrives as many schools are harnessing AI for learning. Public schools in Newark, N.J., have begun using AI-powered Amira Learning to help children learn to read. Educational company NWEA's MAP Reading Fluency platform, a reading-assessment tool for children in pre-K through fifth grade, is used by 2,000 school districts nationwide and more than 1.4 million students; it recently added an AI "coach," which, according to the company, provides "personalized reading coaching based on each student's assessment results." Google has launched the AI learning aid Read Along in Classroom, and Microsoft has both Reading Coach and Math Progress, which use AI to generate problems and check work. Stanford University's Rapid Online Assessment of Reading platform uses AI to assess reading skills and dyslexia. Software company Dystech uses an AI-powered screener to evaluate whether students have learning challenges, and its Dystutor tool uses those results to create personalized practice suggestions.

AI tools for addressing individual differences in learning are arriving at a time when U.S. schools are often unable to fill teaching vacancies. As high schools approached the 2024–2025 school year, 69 percent of them struggled to find fully certified teachers for English as a second language or bilingual education, and 74 percent of elementary and middle schools reported difficulties filling special education teaching vacancies with fully certified teachers, according to the National Center for Education Statistics.

"I see the real potential of a program like Tobey's Tutor in all these areas where [schools] don't have expert instruction for children with learning differences," Gaynor says. "There are a lot of educators who are fearful of AI creeping into the school and our students' work. I see it as a great opportunity for children with learning differences to level the playing field."

Just Keep Plugging Away

For Gajilan, seeing Tobey's enthusiasm and growing confidence affirmed her decision to create the product. "The most heart-wrenching thing was not that my kid couldn't do a math problem or couldn't read an entire chapter without crying—that was upsetting, don't get me wrong," she says. "But the truly upsetting part was him thinking he wasn't good enough to do those things."

Gajilan's own arc bent as she was improving the system. After years as digital news director, she stepped into a new role as global editor for AI development and integration, guiding the Reuters newsroom to use AI to support human work. "Doing this passion project opened my eyes to how profoundly AI is going to change the industry I've devoted my adult life to," she says. "This change is as profound, if not more profound, as when the Internet took over."

And lessons from the platform have returned to Gajilan in other ways. As she was driving Tobey home after a day at work—having spent most of the previous night fixing a bug in the program—a driver cut her off, and she cursed. From the back seat, Tobey asked what was wrong. As she tried to calmly tell him and apologized for swearing, he said he had learned it was important to just keep plugging away. When Gajilan asked where he'd learned that, he said, "Tobey's Tutor." "He was using these phrases I'd never heard him use before," she says. "He was like, 'Look, you just have to keep working the problem. It's not going to be solved right away, but if you keep working at it, you'll get there.'"

Deni Ellis Béchard is *Scientific American*'s senior writer for technology. He is author of 10 books and has received a Commonwealth Writers' Prize, a Midwest Book Award and a Nautilus Book Award for investigative journalism. He holds two master's degrees in literature, as well as a master's degree in biology from Harvard University. His most recent novel, *We Are Dreams in the Eternal Machine*, explores the ways that artificial intelligence could transform humanity. You can follow him on X, Instagram and Bluesky @denibechard https://www.scientificamerican.com/article/how-one-mom-used-vibe-coding-to-build-an-ai-tutor-for-her-dyslexic-son

Arts

- **Poem: ‘$E = mc^2$’**
  Science in meter and verse

Poem: ‘*E = mc²*’

Science in meter and verse

By Elaine Mintzer edited by Dava Sobel & Clara Moskowitz

Masha Foya

I have no faith, but I do believe
in mass–energy equivalence
    I light its candle
    say its prayer
    press my head against its Western Wall

because there is something holy
about an equation
    its insistence on fairness
    on symmetry
    on equal distribution

so when I consider after-life
    when my spirit is cleaved
    from its form

it gives me comfort to think:
  if the constant is not me
  it is, at least, the square
  of the speed of light

  that all parts are accounted for

and when I forget who I am
and when I forget thee
and you forget me
  when the currents of our bodies halt
  when the oceans rest in their beds
  and the great winds give way to calm

then let us believe
the product of our lives
is greater than the sum of us

Elaine Mintzer is a southern California poet and retired high school teacher who finds scientific vocabulary a useful anchor for feelings and philosophy. Her two poetry collections are *Natural Selections* (Bombshelter Press, 2004) and *Drink from the River* (coming soon from Moontide Press).

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https://www.scientificamerican.com/article/poem-e-mc

Cats

- **The incredible, unlikely story of how cats became our pets**
  Two new studies dig into the long, curving path that cats took toward domestication

The incredible, unlikely story of how cats became our pets

Two new studies dig into the long, curving path that cats took toward domestication

By Meghan Bartels edited by Claire Cameron & Sarah Lewin Frasier

Two studies complicate the path that cats' ancestors took to domestication.
Carol Yepes/Getty Images

Cats have taken quite a journey from wild animal to undisputed ruler of millions of couches worldwide.

Scientists long knew the broad outlines of that journey. As humans settled into agriculture and began stockpiling grain, local wild cats sought out these stores as promising places to hunt for rodents. Eventually some humans began encouraging the volunteer pest-control officers, sparking a symbiotic relationship in which both cat and person benefited. Faster than a catnap, felines began changing at a genetic level to become domesticated.

But a pair of new studies, one in *Science* and one in *Cell Genomics*, shows it isn't so easy to herd cats—cat domestication unfolded more slowly and less smoothly than scientists had thought.

“Domestication is a process,” says Leslie Lyons, a feline geneticist at the University of Missouri, who was not involved in either study. “It’s not just that one day all the cats are sitting on your lap.”

SEE MORE: See Stunning Feline Photography Revealing the Science of Cats

Both teams faced the same challenge in their quest to understand how cats pussyfooted their way into humans’ lives—namely, a paucity of archaeological evidence through time. There are several reasons for this lack: For instance, cat bones are very small, and because the animals weren’t on humans’ menu, their remains wouldn’t have been tossed into the garbage piles archaeologists often excavate. In addition, the first signs of domestication are likely to be behavioral or cosmetic changes—such as new tolerance of humans or new coat colors—that are not visible in bones at all.

These complications mean both teams’ reconstructions of feline history are hypothetical and require further investigation; they are not the definitive story of cats. Still, the studies do offer new insights into how these creatures conquered the world.

Barisic Zaklina/Getty Images

Pawing into the Past

For the study detailed in *Cell Genomics*, researchers compared domesticated cats and Asian leopard cats, which are similar in size but have completely different temperaments. (Lyons calls the leopard cats “nasty little kitties.”) The scientists found that the wild cats lived close enough to humans in China for their bones to be discovered at settlements spanning some 3,500 years—but despite all that time, the animals were a “clear example of a ‘failed domestication,’ ” says study co-author Shu-Jin Luo, a biologist at Peking-Tsinghua Center for Life Sciences in China. “Leopard cats returned to their natural habitats, living today as our elusive and hidden neighbors,” Luo says.

Domesticated cats, the study suggests, finally flourished in China only by following the Silk Road, arriving there from the Near East around 1,400 years ago. The Asian leopard cats had retreated from human settlements perhaps a couple of centuries earlier, possibly because climate change led to agricultural and population shifts in the region that reduced the amount of food available, the researchers say.

The other paper, published in *Science*, focuses on cats in Europe, the Near East and North Africa. It builds on previous research of mitochondrial DNA, which is passed from mother to offspring within the power plants that keep cells operating. That analysis had suggested that the ancestors of domestic cats were a blend of Near Eastern and North African wild cats.

For the new research, the scientists analyzed samples of nuclear DNA—the main genome of an organism, containing both parents’ contributions—from some of the same specimens that were examined in the older study, for which nuclear DNA analyses weren’t feasible then. Particularly intriguing was a new view of cats that lived in Turkey thousands of years ago, which the researchers had expected to be domesticated. “I was so excited to have a look at their nuclear genomes for the first time," says Marco De Martino, a paleogeneticist at the University of Rome Tor Vergata and lead author of the study.

The new analysis indicated something quite unexpected: these Neolithic felines were pure wild cat. The finding, similarly to the results of the analysis done in China, suggests that cats lingered aloofly near humans with only superficial relationships for thousands of years before domestication.

"Cats are a complex species; they are independent," says Claudio Ottoni, a paleogeneticist at the University of Rome Tor Vergata and senior author of the *Science* study. "They were not just staying with humans—they would still go around and mix with local wild cats."

Both findings lend weight to the idea that truly domesticated cats arose and spread far later than previously believed, perhaps as late as 2,000 years ago. If that timeline is correct, it underscores just how rapidly cats have settled into the human world after their stop-and-go history—for comparison, dogs have been making puppy eyes at humans for close to 11,000 years—and how much we have to learn about our feline friends.

"They're just [cracking] the door open a little bit at a time, just a whisker's length, to give us ideas of how they got where they are," Lyons says.

Meghan Bartels is a science journalist based in New York City. She joined *Scientific American* in 2023 and is now a senior reporter there. Previously, she spent more than four years as a writer and editor at Space.com, as well as nearly a year as a science reporter at *Newsweek*, where she focused on space and Earth science. Her writing has also appeared in *Audubon*, *Nautilus*, *Astronomy* and *Smithsonian*, among other publications. She attended Georgetown University and earned a master's degree in journalism at New York University's Science, Health and Environmental Reporting Program.

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https://www.scientificamerican.com/article/the-incredible-unlikely-story-of-how-cats-became-our-pets

Culture

- **A bright light in the dark**
  The Nobel Prizes remind us how science can unite society and inspire hope for the future
- **Readers respond to the October 2025 issue**
  Letters to the editors for the October 2025 issue of Scientific American

A bright light in the dark

The Nobel Prizes remind us how science can unite society and inspire hope for the future

By David M. Ewalt edited by Jeanna Bryner

Scientific American, February 2026

In December I was in Stockholm, Sweden, for the Nobel Prize award ceremony, a celebration of science and discovery that feels like a national holiday in that country. The week leading up to the awards is stacked with lectures, concerts, exhibitions and discussions, and Stockholm is decorated with light displays and video shows.

The whole thing feels like the Oscars. People line up on the street to catch a glimpse of celebrities as they leave the Stockholm Concert Hall. National public television dedicates more than five hours to a live broadcast of the ceremony and subsequent banquet. Huge numbers of Swedes tune in not just for the glamour but to hear interviews with researchers, learn about medical breakthroughs, and explore advances in fields such as materials science and quantum physics.

It’s inspiring. It gives me hope that a general populace can still get excited about science and support it. That’s a stark contrast to what we’ve seen in the U.S., where science has endured an annus horribilis: research funding slashed, government support dwindling, and growing segments of the population embracing misinformation and rejecting scientific consensus.

At the banquet, one of my tablemates—a vice chancellor from a major Swedish university—expressed concern about these trends. She told me she had a meeting planned with other European university leaders in the new year, where they would discuss how to respond to future attacks on science, using the U.S. and Hungary as their cautionary examples.

Yet the work honored in 2025 offers a profound counternarrative to that despair. It has given us tools to reshape our reality. The physics prize recognized research into macroscopic quantum-mechanical tunneling, paving the way for quantum computing. The chemistry laureates developed porous materials capable of capturing carbon dioxide and storing hydrogen—vital technologies for our climate future. And the prize in physiology or medicine paid tribute to the discovery of mechanisms to prevent the immune system from attacking healthy organs, offering hope for autoimmune and cancer therapies.

These breakthroughs remind us that science is, as Astrid Söderbergh Widding, chair of the Nobel Foundation, stated in her opening address, “a lingua franca for humankind” that transcends borders and divisions. The Nobel awards remind us that science is what will make it possible to address and come to terms with the many global challenges we face.

The prizes also remind us of our responsibilities. The Nobel lights in the dark Scandinavian winter tell us we cannot be passive spectators. We must be active contributors in defending the freedom of research. If annual science awards can hold the attention of a European nation, then surely we can work to rekindle that same spirit of possibility here at home.

This issue’s cover story, written by *Scientific American* associate editor Allison Parshall, illustrates one opportunity for science to light the way for society: scouring the brain for the origins of consciousness. As artificial-intelligence models claim sentience and researchers increasingly scrutinize the minds of animals, the abstract debates of philosophy are being transformed into urgent questions. Although the field currently faces an “uneasy stasis” marked by bruised theories and heated debates, the commitment to solving these mysteries stays fierce.

This pursuit mirrors the spirit I witnessed in Stockholm. Whether we are peering into the universe inside a human brain or developing materials to protect our climate, science remains our best tool for navigating the unknown. As we celebrate the tangible breakthroughs of the Nobel laureates, we must also champion the messy, difficult and vital work of those attempting to explain the one experience we all share: the “singular sense of awareness” that makes us who we are.

David M. Ewalt is editor in chief of *Scientific American*.

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https://www.scientificamerican.com/article/a-bright-light-in-the-dark

Readers respond to the October 2025 issue

Letters to the editors for the October 2025 issue of Scientific American

By Aaron Shattuck

Scientific American, October 2025

WEALTH AND KNOWLEDGE

In "Billionaire Science, for Better or Worse" [From the Editor], David M. Ewalt suggests that with cuts to government funding, "many researchers are going to have to rely on business—and, yes, billionaires." He also cautions that such "billionaire science" can go wrong.

Most, if not all, self-made billionaires exploited a singular focus in their field with limited diversification. This offers both risks and opportunities in science. As a recovering academician, I've found that the pressure to publish articles for advancement in the context of bureaucracy and limited funding has led to research efforts tailored toward the most likely source of funding—and that do not seek to answer unique questions.

New sources of funding from individuals or family offices should serve to accelerate innovation in resource-rich environments with passionate inventors, scientists and academics. As long as the latitude to explore stays constant and the intentions of the sponsors remain in the public interest, I foresee a net positive impact. Recruiting more billionaires who might otherwise not have invested in scientific endeavors could fuel additional advancements.

JONATHON JUNDT *VIA E-MAIL*

As a long-time subscriber and a poet whose poem "Extravehicular Activity" appeared in your April 2023 issue [Meter], I'd like to offer my take on billionaire science as a prose poem:

The problem with billionaire science is billionaires are smart enough to make boatloads of money and stupid enough to think making boatloads of money also makes them universal geniuses who know everything about everything and who therefore do not need to give prolonged attention to anything besides making boatloads of money.

HOWARD V. HENDRIX *VIA E-MAIL*

DEEPWATER EFFICIENCY

In "Drink Deep" [Advances], Vanessa Bates Ramirez reports on efforts by Norwegian start-up Flocean, led by CEO Alexander Fuglesang, and other companies to remove salt from seawater in the deep sea.

The article states that the higher water pressure in such deep water can make desalination via reverse osmosis more efficient. But even with the higher pressure, the pressure on both sides of the filtering membrane would be the same. Some kind of pump would be needed to reduce the pressure on the freshwater side to make the procedure work. So you are right back to where you were with standard reverse osmosis: needing to use power to maintain the pressure difference to generate the filtering process. I don't see how this is any more efficient.

WILLIAM J. MILLS *BREWSTER, MASS.*

FUGLESANG REPLIES: *Mills is correct that reverse osmosis works only if you maintain a pressure difference across the membrane and that you need pumps to achieve that. We do not eliminate the need for pumps, but we leverage the pressure to greatly reduce energy demand.*

What changes in a deepwater installation is where the pressure comes from and where you apply it. At a depth of several hundred meters, the seawater is already at very high absolute pressure. Instead of taking low-pressure seawater at the surface and using a large pump to push the entire feed stream up to high pressure, we can place the high-pressure pump on the permeate side of the membrane. This allows us to focus our pumping work on the product freshwater stream. We leverage the reduced volume of pumping only freshwater to cut energy emissions by 30 to 50 percent. In addition, we avoid some of the large, high-pressure surface equipment a conventional plant requires.

Last, moving water upward underwater does not cost energy. The ocean itself provides counterpressure. We "lift" water only when it leaves the sea.

DUST IN THE LIGHT

As Richard Panek notes in "The Cosmos Revised" [September 2025], researchers' distance calculations to determine the universe's expansion rate have used the known brightness of celestial bodies such as type Ia supernovae.

There must be dust in the millions or billions of light-years of distance from Earth and thus in the early universe. How is the attenuation of light caused by such dust accounted for in these calculations?

AL SPENCER *VIA E-MAIL*

PANEK REPLIES: *Astronomers account for dust by examining the unequal amount by which it scatters—that is, redirects the path of—light at different frequencies. For instance, a supernova appears various degrees of red for the same reason a sunset appears red: the scattering of light because of particulates. In the case of the 1990s discovery of evidence that the expansion of the universe is accelerating (via what we now call dark energy), the two collaborations relied on a method developed by researchers Adam Riess, William Press and Robert Kirshner. As they wrote in a 1996 paper, their method uses multicolor light-curve shapes, or MLCS, "to estimate the luminosity, distance, and total line-of-sight extinction of type Ia supernovae."*

GIVE FUSION A CHANCE

In "Fusion Dreams," by Clara Moskowitz and Matthew Twombly [Graphic Science], Laura Berzak Hopkins of the Department of Energy's Princeton Plasma Physics Laboratory is quoted as saying, "I'm confident that we need fusion [energy], so that makes me very confident that we will solve fusion."

Do the energy demands the article cites as "high and getting higher" mean fusion reactors must be possible? Might it be possible that a practical fusion reactor is impossible? Efforts to develop such reactors may be justified, but unless and until they are proved possible, it would be prudent to remind ourselves that they may never be developed. We ought to act on the need to reduce our energy demands until fusion reactors are actually operational. Necessity may be "the mother of invention," as Berzak also noted, but some would-be mothers never have children.

DICK WALTON *BILLINGS, MONT.*

MOSKOWITZ REPLIES: *Walton makes a good point. But I believe Berzak Hopkins feels confident both because fusion is necessary and because it is possible. The challenges at this point are in engineering and logistics—not in the physics. Scientists understand enough about fusion to know already that it is possible, which is why many feel so motivated to make it a reality.*

Aaron Shattuck is a senior copy editor at *Scientific American*.

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https://www.scientificamerican.com/article/readers-respond-to-the-october-2025-issue

Dogs

- ## Which dog breed stereotypes are true? Here’s the science

  A large dataset shows some dog stereotypes are based in reality, and others might be unfair characterizations

From anxious Weimaraners to aggressive Chihuahuas: What science can tell us about dog breeds

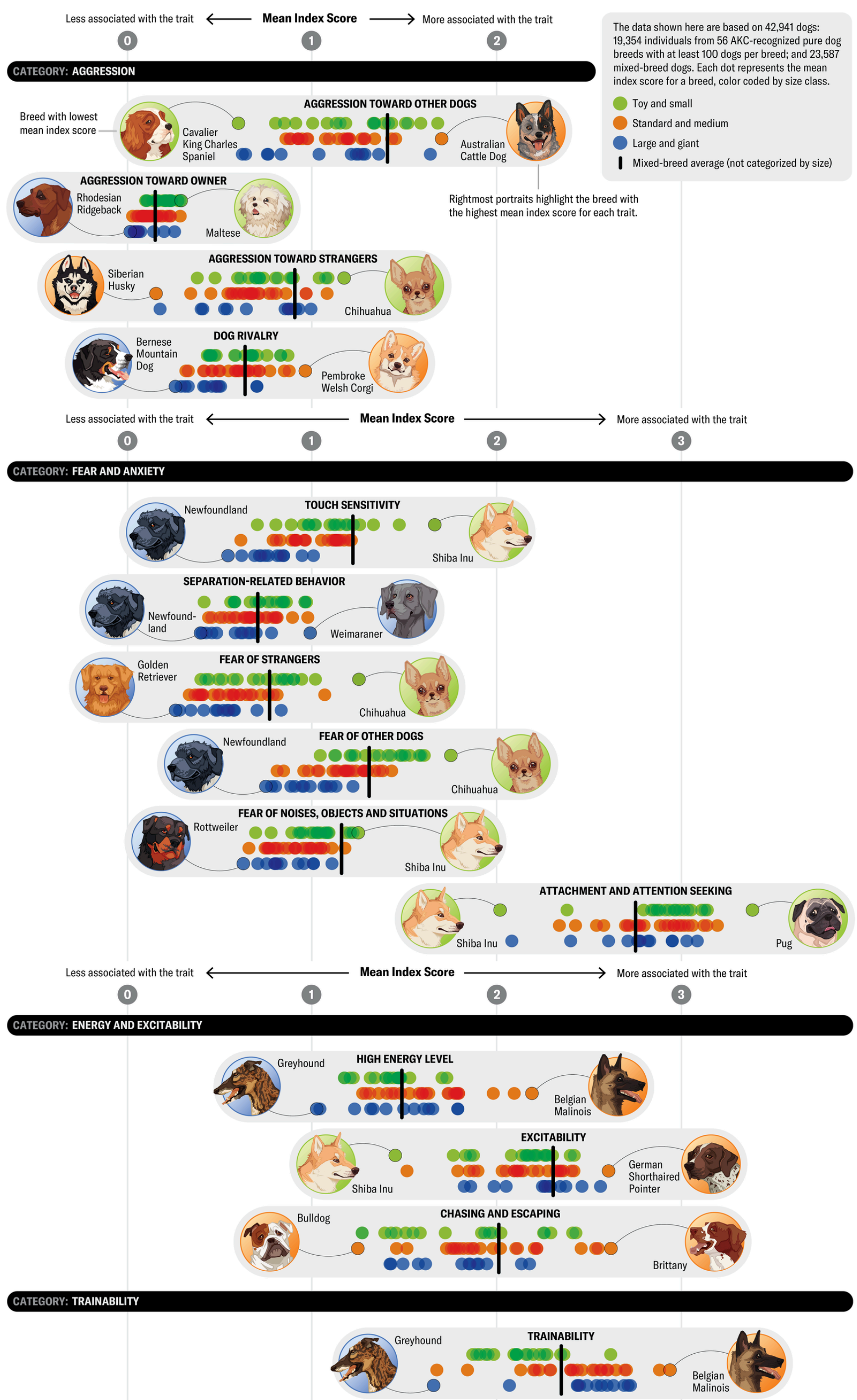
A large dataset shows some dog stereotypes are based in reality, and others might be unfair characterizations

By Humberto Basilio, Miriam Quick, Jen Christiansen & Lee Lotor edited by Clara Moskowitz & Jen Christiansen

Lee Lotor and Jen Christiansen

Dogs can have wildly different personalities, which often vary by breed and size. Although individual temperament matters most, larger trends can help predict which pooch will be meek and mild and which is most likely to bite the postal worker.

The Dog Aging Project, a long-term study on canine aging, has collected data on dog behavior from more than 50,000 owners, distilling the results into scores for traits such as trainability, excitability and aggression. Owners of mixed-breed dogs reported higher average scores for fear and aggression than owners of single-breed dogs, for instance. And compared with larger dogs, smaller dogs tended to score higher for fear, aggression and excitability and lower for trainability. Understanding these patterns is key to improving the compatibility of people and their pets. "Dogs are entirely dependent on their owner," says veterinarian Audrey Ruple of the Virginia-Maryland College of Veterinary Medicine, a collaborator on the Dog Aging Project. A mismatch can be "devastating," but a good match can ensure dogs receive the care and affection they need.



Miriam Quick, Lee Lotor and Jen Christiansen; Source: Dog Aging Project (DAP) *https://data.dogagingproject.org/Index* (*data*)

SMALL DOG SYNDROME

Dog breeds classified as toy or small have higher owner-rated scores on aggression and fear, as well as lower trainability scores. Large and giant dog breeds, in contrast, are on average the most trainable and the least aggressive and anxious. “I suspect it has to do with the way small dogs are treated as compared with large dogs,” Ruple suggests. Good behavior in a big dog is often judged as more of a necessity, whereas people may let little dogs off the hook.

OLD DOGS, NEW TRICKS

Dogs rated as more trainable tend to learn new skills more readily. They often obey “sit” or “stay” commands immediately, and they aren’t as easily distracted by interesting sights, sounds or smells. Some breeds are known for being easily taught, and mixed-breed dogs tend to get rated as less trainable than purebreds. That pattern, however, might reflect the early life experiences of mixed-breed dogs, who often are adopted from shelters or rescues and have experienced trauma, Ruple says. A purebred dog raised by a reputable breeder, however, will be primed to be comfortable around people and eager to learn.

Humberto Basilio is a Mexican science journalist covering policy, health, misconduct, archaeology and the environment. He is also a former news intern at *Scientific American.* His work has been published in the *New York Times*, *National Geographic*, *Science*, *Nature*, and more.

Miriam Quick is a data journalist who investigates scientific, environmental, economic and cultural issues. Her analyses and storytelling have been featured by major international media outlets, including the BBC, the *New York Times*, *Scientific American* and Sentient Media. Her book *I Am a Book. I Am a Portal to the Universe* (Particular, 2020), co-authored with Stefanie Posavec, won the Royal Society Young People’s Book Prize 2021.

Jen Christiansen is acting chief of design and senior graphics editor at *Scientific American*, where she art directs and produces illustrated explanatory diagrams and data visualizations. She is also author of the book *Building Science Graphics: An Illustrated Guide to Communicating Science through Diagrams and Visualizations* (CRC Press). 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 @jenchristiansen.com

Lee Lotor is an independent artist, based in the western U.S., who creates digital art inspired by native North American ecosystems and wildlife. Lotor strives to increase awareness for conservation through unique and creative artwork that highlights the interconnectedness of the natural world.

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https://www.scientificamerican.com/article/which-dog-breed-stereotypes-are-true-heres-the-science

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Health

- **Heal injuries faster with new science**
  Motion is the new potion, and rest is no longer the best

Heal your injuries faster than ever

Motion is the new potion, and rest is no longer the best

By Lydia Denworth edited by Josh Fischman

Jay Bendt

This article was made possible by the support of Yakult and produced independently by Scientific American*'s board of editors.*

After a slip on the ice, a sports injury, even surgery, most people's instinct is to rest what hurts. "When you have an acute injury, your body is sending signals through the peripheral and central nervous systems and the immune system to say, hold on, I need to stop doing this so we can allow the tissue to heal," says Ericka Merriwether, a physical therapist and pain researcher at New York University. Rest, after all, is the first part of the familiar RICE therapy, which stands for "rest, ice, compression and elevation."

But experts no longer believe RICE is the best strategy for recovery. They especially quibble with the first step: rest. Even Gabe Mirkin, the sports medicine physician who coined the RICE acronym in 1978, has acknowledged that newer evidence suggests other approaches are more effective.

Resting an injury can alleviate pain and may be necessary in the short term, especially for injuries such as muscle tears, which might be exacerbated by movement. In most cases, however, limiting movement does not promote healing. In fact, immobilization causes muscles to weaken and lose stability. An injured body part that is immobilized for too long is more likely to move from acute to chronic pain (that is, pain that lasts more than three months).

Instead of rest, “motion is the potion,” experts say.

Instead of rest, “motion is the potion,” experts say. And it is important to move far sooner than many imagine. Once a physician determines that movement is safe and that there’s no biological reason not to engage in it, it’s a case of “use it or lose it,” says Rianne van Boekel, a nurse and associate professor at the Radboud University Medical Center in the Netherlands whose research focuses on acute and transitional pain.

Studies bear out the early-movement idea. In a controlled trial of athletes with serious soft-tissue injuries, researchers found that those who started rehabilitation two days after an injury instead of nine days later were able to return to sports 20 days sooner (in 63 days rather than 83). In a separate study, those who engaged in progressive agility training rather than static stretching were less likely to reinjure themselves. And in people with low back pain, consistent movement and exercise can improve pain levels, range of motion, strength and tissue repair.

That helps to explain why a popular acronym to emerge as a replacement for RICE is POLICE, in which the O and L stand for “optimal loading,” or putting stress on tissues to induce the cellular changes that optimize recovery. (The other letters stand for “protection,” “ice,” “compression” and “elevation,” so some parts of the RICE approach still hold.)

Putting stress on injured tissues does hurt, and the relation between pain and movement is complex. A person’s responses to pain strongly influence their recovery from injury, researchers say, because the perception of pain has social and psychological elements as well as biological ones.

Injured tissue sends signals to the brain, which is where we perceive pain. “People say pain is in your head, and yes, it is,” Merriwether says. There are also descending pain pathways from the brain back to the periphery of the body that inhibit and modulate the perception of pain.

That is why social environments and psychology play roles. Studies indicate that family caregivers might delay recovery if they do too much for an injured loved one, says anesthesiologist and pain researcher Esther Pogatzki-Zahn of the University of Münster in Germany. And, she says, people who must carry on with their lives—taking care of children or returning to work—often report lower levels of pain than people who don’t. On the psychological front, anxiety is a major risk factor for developing chronic pain after an injury. The more someone fears pain, and the more they avoid moving because of it, the worse they usually become.

To encourage movement and the healing it can bring, pain experts are working to educate people. “Pain reduction is the goal,” Pogatzki-Zahn says. In a 2025 randomized controlled trial of 150 people, nurses delivered one two-hour virtual lesson on pain and nonpharmacological ways to relieve it. Such approaches can include distraction, mindfulness and virtual-reality exercises. Patients who received the pain intervention scored significantly lower on measures of pain catastrophizing after eight weeks than those who were put on a wait list for the class. The first group also had better scores on pain intensity, depression, pain self-efficacy, fatigue and satisfaction with social roles. “The best way to deal with pain is to accept that you are in pain,” van Boekel says.

Painkillers can also help, although the goal should be to take the least amount of medicine for the shortest time possible, van Boekel notes—“enough to be able to move, not to get rid of all the pain.” And she advises taking acetaminophen (Tylenol) rather than ibuprofen (Advil) because it has no side effects at correct dosages.

Researchers are also paying closer attention to how pain is assessed. For instance, the latest studies suggest that clinical evaluations should more carefully distinguish between pain at rest and movement-evoked pain because it turns out patient outcomes can vary according to which type of pain they experience.

There is far more to understand about the role of pain and movement in recovery, but for now it seems fair to call on another familiar saying: no pain, no gain.

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

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https://www.scientificamerican.com/article/heal-injuries-faster-with-new-science

History

- **February 2026: Science history from 50, 100 and 150 years ago**
  Giant atoms; corpses for science

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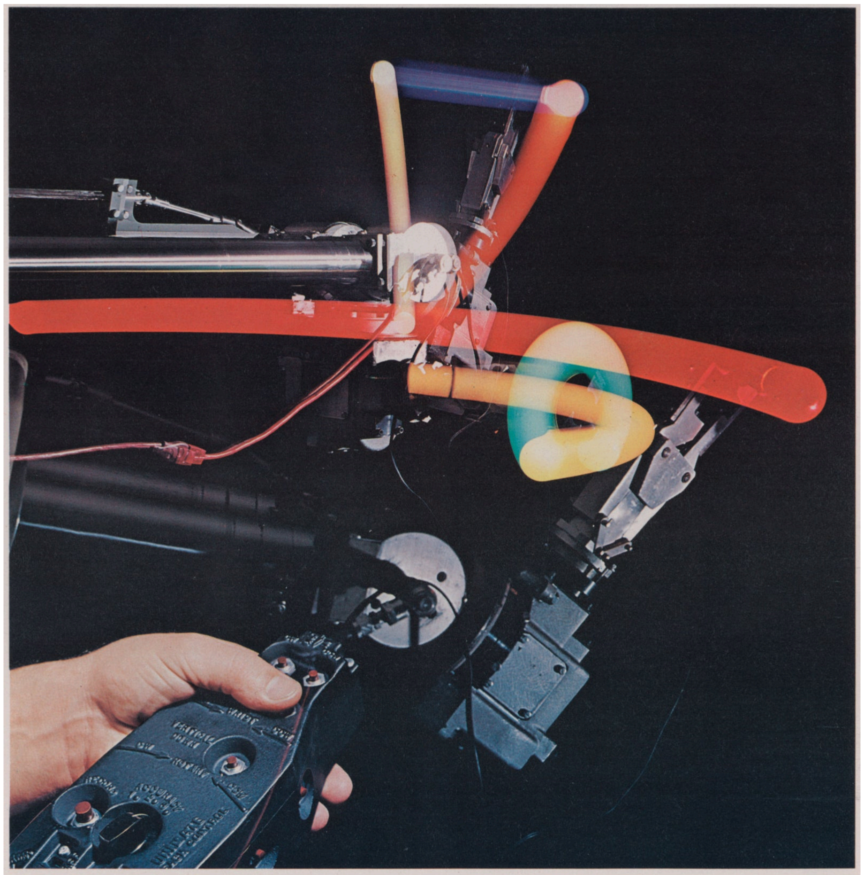
February 2026: Science history from 50, 100 and 150 years ago

Giant atoms; corpses for science

By Jeanna Bryner



1976, Industrial Robot: Made by Unimation, Inc., of Danbury, Conn., the Unimate robot can execute six basic motions. In this multiple-exposure photograph, the robot's gripper, or hand, is holding lights of different colors to distinguish the six motions. The pistonlike arm is capable of three motions: in-out (*blue*), up-down (*white*) and left-right (*red*). At any position of the robot's arm, the gripper can execute three more motions: bend (*orange*), swivel (*green*) and yaw (*yellow*). *Scientific American*, Vol 234, No. 2; February 1976

1976

Giant Atoms

“The biggest atoms are not those of some heavy, transuranic element but quite light atoms in a highly excited state. Although the diameter of a normal atom is about 10^{-8} centimeter, some excited atoms have a diameter of 10^{-5} centimeter and are as large as certain bacteria. The energy state of an atom is denoted by its principal quantum number, designated *n*, which defines the probability of finding an electron at a particular distance from the nucleus. In the state of lowest energy, *n* is 1, and the electrons are effectively confined to a quite small volume. At higher energy states, *n* increases as electrons are likely to be found at larger distances from the nucleus. Interest in such inflated atoms has been aroused in part by new methods for creating, manipulating and detecting them. Atoms have now been prepared in the laboratory with *n* as high as 105. Such atoms are on the very brink of ionization, and with only a small input of energy, they fly apart.”

1926

What Is Life?

“We are so far from a perfect understanding of life that even active workers in biological research cannot agree as to the real nature of life—whether it is purely a matter of chemistry and physics and evolution and chance, or whether there will indeed prove to be an element of the nature of the ‘spark of life’ of the ancients, transcending mortal understanding. It is now generally known that the unit of living matter is the cell. The cell is the building stone, the brick, from which all plants and animals are constructed. Life may indeed be regarded as the resultant action of the cells of which the organism is composed. What more natural, then, than to concentrate attention on the single cell? There is little doubt that these microscopic objects hold the key to the full understanding of life.”

Worldwide Wireless Net

“The various colonies of the British Empire are being linked by a new short-wave beam transmitter, which concentrates radio energy as a searchlight reflects light in a definite and desired direction. Finishing touches on installations of this up-to-date system are being made near Montreal, by the Marconi Wireless Telegraph Company of Canada, for direct communication with England and Australia. These Canadian beams will be the first links to be forged in the worldwide wireless net. The Canadian Marconi Company will construct a beam station in the Dominion of Canada for communication with stations to be built in England. Each station is to be capable of communication at a speed of 100 five-letter words per minute each way, during a daily average of 18 hours.”

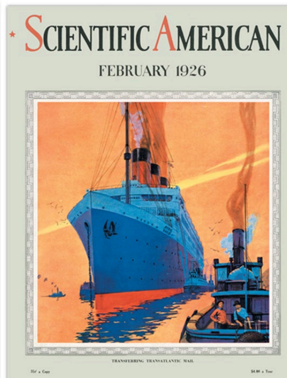
Point of View: Is Science Callow?

“What science needs most today is a true vision rising above spectrometers, cell walls, vapor tensions, microtomes and polarities, and seeing beyond them—as far as man can hope to see—the end toward which all these humbler things are but little steps. Such a vision is that of Professor Theodore D. A. Cockerell of the University of Colorado—biologist, zoologist, entomologist of note, but known, because of his writings, to all the biological world as ‘the Huxley of America’; a man who has made of a little corner of science a true philosophy, who has brought to those who care more for life itself than for a test tube full of green precipitate, a foreshadow of what science, under better guidance than that of our day, might mean to the ‘man in the street.’”

1876

Shall We Undergo Dissection?

“To yield up our lives for the advancement of Science is something that few of us would be willing to do, but to yield our bodies as a sacrifice on the altar of truth and knowledge, after we no longer have any use for them, is not a very hard thing; and therefore we are not surprised to read that a society has been formed in Paris, the members of which bind themselves, by a special testamentary disposition, not to be interred after death. Their bodies are to be delivered to the dissecting rooms of the various medical schools for dissection. We are not afraid that the whole world will follow this example and flood the market with useless corpses. There will still remain those who desire an old-fashioned burial.”



Jeanna Bryner is executive editor of *Scientific American*. Previously she was editor in chief of Live Science and, prior to that, an editor at Scholastic's *Science World* magazine. Bryner has an English degree from Salisbury University, a master’s degree in biogeochemistry and environmental sciences from the University of Maryland and a graduate science journalism degree from New York University. She has worked as a biologist in Florida, where she monitored wetlands and did field surveys for endangered species, including the gorgeous Florida Scrub Jay. She also received an ocean sciences journalism fellowship from the Woods Hole Oceanographic Institution. She is a firm believer that science is for everyone and that just about everything can be viewed through the lens of science.

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https://www.scientificamerican.com/article/february-2026-science-history-from-50-100-and-150-years-ago

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Language

- **Science crossword: Consciousness carriers**
  Play this crossword inspired by the February 2026 issue of Scientific American

Science Crossword: Consciousness Carriers

By Aimee Lucido

This crossword is inspired by the February 2026 issue of Scientific American. *Read it here. Print readers, check your answers by selecting "Assist" above, and then "Reveal Grid," or "Print" and then choose "Solution."*

We'd love to hear from you! E-mail us at games@sciam.com to share your experience.

Aimee Lucido makes crosswords part-time for several outlets and writes trivia full-time for Bloomberg's news quiz, Pointed. She is also the author of several books for kids, including *Emmy in the Key of Code*, *Recipe for Disaster*, and *Pasta Pasta Lotsa Pasta*. Lucido lives with her husband, daughter and dog in New York.

https://www.scientificamerican.com/article/science-crossword-consciousness-carriers

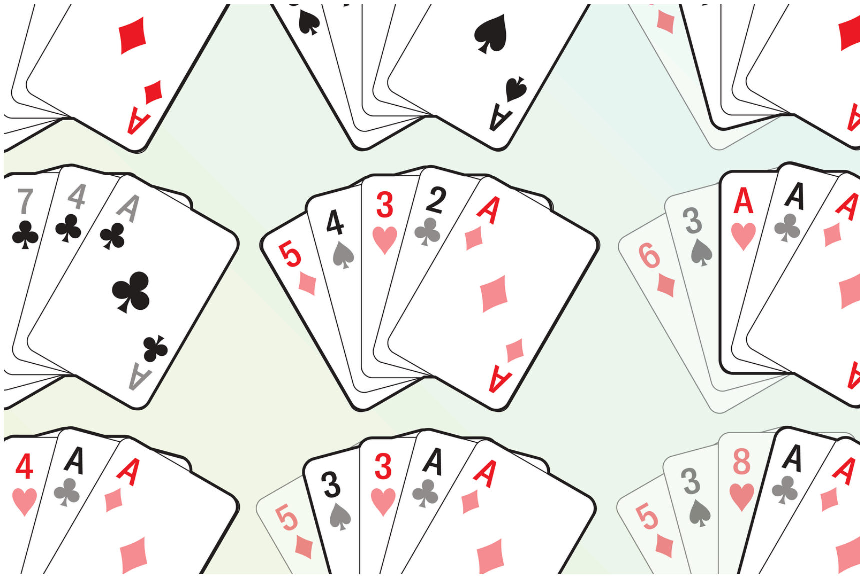
Mathematics

- ## Why 52 cards is the perfect number for poker—mathematically
  A traditional card deck happens to dodge a tricky poker paradox. Other poker variants aren't so lucky
- ## Math puzzle: A winning loser
  Pick an unusual winning poker hand in this math puzzle
- ## The math mystery that connects Sudoku, flight schedules and protein folding
  Thousands of notoriously difficult problems in computer science are actually the same problem in disguise

The math behind a perfect poker deck

A traditional card deck happens to dodge a tricky poker paradox. Other poker variants aren't so lucky

By Emma R. Hasson edited by Sarah Lewin Frasier


Amanda Montañez

What's the perfect number of cards for playing poker? According to a new mathematical discovery, the answer is the traditional 52. Almost.

In Texas Hold'em poker, players wager on the best five-card hand they can make among the two cards in their hand and the communal ones on the table. Hands are ranked based on their probability of occurring. A full house, for example, with three cards of the same value (fives or kings, for instance) and two cards of another, is less likely than a flush with any five cards of the same suit. A full house therefore beats a flush. In short-deck poker, a variant that removes cards numbered 2 through 5 (called "ranks 2–5"), there are fewer cards of each suit and a flush becomes less likely than a full house. In a recent paper posted to the preprint server arXiv.org, computer scientist Christopher Williamson examines how the game of poker changes as the number of cards per suit increases or decreases. Depending on that number, an interesting paradox can occur, Williamson found—one that's nearly always avoided in games with a 52-card deck with 13 in each suit.

After a bidding process, poker players will declare their best hands in what's called the "showdown." Consider two hands: a one pair, which has one pair of cards with the same value, and a two pair, with two pairs of such cards. In short-deck poker, although a two pair is less likely to appear than a one pair, its showdown probability—the likelihood that it will be the best hand someone has—is actually higher than that of a one pair. If the hand rankings were adjusted to account for this, no one would ever play a two pair over a one pair, which would change its showdown probability once again.

Amanda Montañez

"Thirteen is kind of the sweet spot," Williamson says regarding how many cards a deck should have in each suit. It's the smallest number for which the showdown ranking actually matches the standard ranking for all hands other than a single high card (the lowest-ranking hand). Although the usual number of cards in a deck is purely historical—it's said to symbolize 52 weeks in the year and the four seasons—Williamson was delighted to find a more mathematical justification. There is only one superior setup, which would keep all rankings aligned to their showdown probabilities, including the high card: you'd need 23 cards in each suit, nearly twice as many as in the traditional deck.

Nikita Luther, a top professional poker player, finds the result fascinating. "It's so complex, the way the variables interact with each other," she says. Luther says she hasn't deeply explored variants beyond Texas Hold'em; even there, "I could spend the rest of my life just trying to understand this game."

Try a related math puzzle here.

Emma R. Hasson is *Scientific American's* Games ace and a Ph.D. candidate in mathematics at the City University of New York Graduate Center with expertise in math education and communication. Hasson was also a 2025 AAAS Mass Media Fellow at *Scientific American*.

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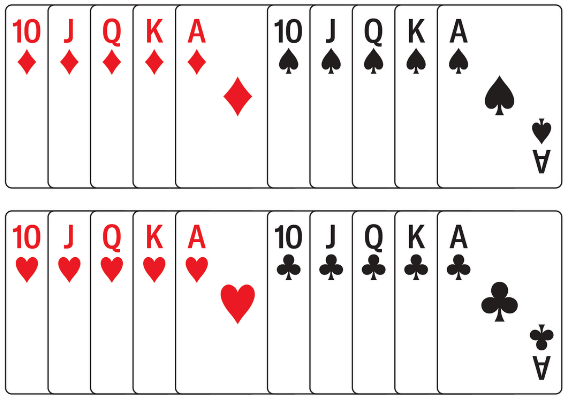
https://www.scientificamerican.com/article/why-52-cards-is-the-perfect-number-for-poker-mathematically

Math puzzle: A winning loser

By Emma R. Hasson



Amanda Montañez

If the cards shown here are rearranged to form four new poker hands of five cards each, what is the lowest possible winning or tying hand?

When two hands are of the same type, such as a pair or a flush, first check the cards involved in the pattern. The higher rank wins—for instance, KKKK10 beats QQQQJ. If the cards involved are the same, check the next-highest card in the hand—KKAJ10 beats KKQJ10. If the hands are exactly the same except for the suit, it's a tie.

If you need a refresher on the poker hands, see the graphic below. (And for more on poker strategy, check out our tie-in article: The Math behind a Perfect Poker Deck

Amanda Montañez

The lowest possible hand overall is 10 10 JQK. Because there are only five ranks, picking five different cards in a hand to avoid a pair will necessarily result in a straight (five cards in a row).

The lowest possible winning hand has the cards in this configuration, where hands 3 and 4 are tied for winner:

Hand 1: 10 10 QKA
Hand 2: 10 10 QKA
Hand 3: JJQKA
Hand 4: JJQKA

We'd love to hear from you! E-mail us at games@sciam.com to share your experience.

Emma R. Hasson is *Scientific American's* Games ace and a Ph.D. candidate in mathematics at the City University of New York Graduate Center with expertise in math education and communication. Hasson was also a 2025 AAAS Mass Media Fellow at *Scientific American.*

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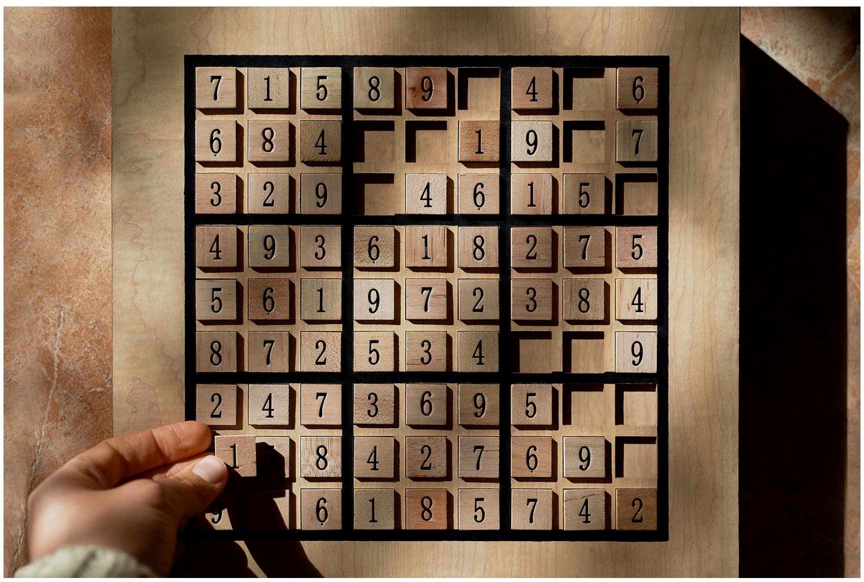
https://www.scientificamerican.com/article/math-puzzle-a-winning-loser

The math mystery that connects Sudoku, flight schedules and protein folding

Thousands of notoriously difficult problems in computer science are actually the same problem in disguise

By Jack Murtagh edited by Jeanna Bryner



With NP-complete problems, you could discover a fast algorithm to solve Sudoku puzzles that could also break the encryption schemes that protect our digital economy.
Natalia Barliaeva/Getty Images

Sudoku fan? After diving into the math behind the game, test your skills with our very own puzzles in SciAm Games!

Computer science seemingly rides a curve of unstoppable progress. Mere decades took us from vacuum tubes to microchips, from dial-up to high-speed Internet, and from Office Assistant Clippy to ChatGPT. Yet thousands of everyday problems across science and industry remain just as unsolvable as ever for today's fleet of supercomputers powered by artificial intelligence.

People working on these notoriously hard "NP-complete" problems could win a million-dollar prize, awarded by the nonprofit Clay

Mathematics Institute, for either finding their fast solution or proving that none exists. An amazing insight from the 1970s makes this challenge even more tantalizing: these 1,000-plus problems are, in a deep sense, one and the same. If you solve one, you solve them all. This concept, now fundamental in the field of theoretical computer science, shows that certain groups of computational problems form a unified web. Discover a fast algorithm that solves Sudoku puzzles of any size, and you can now break the encryption schemes that protect our digital economy. Reveal a shortcut for scheduling a flight tour within a budget, and you can use it to solve nearly any famous open math problem.

Finding fast algorithms for these NP-complete problems (or proving that no such algorithms exist) would resolve the “P versus NP” question, which is the most important mystery in computer science. P refers to the set of computational problems that computers can solve efficiently. Set NP, meanwhile, contains the problems whose solutions can be verified efficiently—but these problems can’t necessarily be solved quickly. NP includes everything in P (because finding a solution is a perfectly good way to verify that solution), as well as harder problems for which we don’t know efficient methods for finding solutions. We can verify them only once they are solved. The P-versus-NP question asks whether this apparent asymmetry between finding a solution and verifying one is real or illusory. Maybe P = NP, and they refer to the same set of problems. In other words, maybe the NP problems that we don’t know how to solve efficiently only appear hard relative to P problems because we have yet to find the right insights.

For example, given a budget, any large list of cities and the connecting flights between those places, is there an algorithm (a recipe of simple instructions) that would efficiently decide whether you can visit all the cities while respecting the budget? We don’t know. We do know an inefficient algorithm: check every possible sequence of flights that takes you to all the cities, add up the cost of each, and compare the totals with the budget. But as the number of cities on the list grows, the number of routes to check explodes exponentially, quickly growing infeasible even for the fastest computers. There may or may not be some clever shortcut that circumvents this exhaustive search, but computer scientists have yet to find one. Given a solution, however—in this case, a proposed list of flights—one could verify in a reasonable amount of time whether a route hits every city and stays under budget. If P equals NP, the flight scenario (an example of what is called the traveling salesperson problem) presumably has a speedy solution. We just don’t know it yet.

Many natural computational problems join the traveling salesperson problem in the NP set. This includes challenges from logistics (such as packing boxes into trucks), social networks (finding cliques of mutual friends), biology (predicting how proteins will fold), and games such as Sudoku, Pokémon and Candy Crush. We can even cast math itself as an NP problem because its proofs can be verified efficiently. It may seem strange to classify these as “hard” problems when people pack boxes into trucks and solve Sudokus every day. But we consider an algorithm to have solved a problem efficiently only if it solves every instance efficiently, including very large ones. Of course, a computer can solve a 9 × 9 Sudoku faster than a one-million-by-one-million Sudoku, so the rigorous definition of “efficient” appeals to how the time required to solve a problem scales with the size of the input.

The P-versus-NP question concerns a variety of computational problems and how they relate to one another, so it may seem like a resolution would require investigating each of those problems individually. Say you were to find an efficient algorithm for the traveling salesperson problem. This discovery would be a heroic breakthrough, but would it tell you anything about your ability to solve huge Sudokus or any other challenging NP problem? Amazingly, your algorithm for that single problem would fully resolve P versus NP.

In 1972 computer scientist Richard M. Karp published a seminal paper demonstrating that 21 classic NP problems have a remarkable property: an efficient algorithm for solving any one of them could be used not only to solve the other 20 but to solve every problem in NP. He called these 21 problems NP-complete. In the intervening years, that list has grown as researchers discovered many other NP problems that share this magic property (including the traveling salesperson one).

We can view NP-completeness with optimism or pessimism. On the optimistic hand, a fortress of monstrously difficult problems standing between us and untold technological promise now looks more like a house of cards. Yank one into the realm of feasibility, and the entire NP edifice collapses; then a scientific revolution rises from the rubble, filled with effortlessly efficient travel, rapid drug discovery via protein folding, and a new age of mathematics. On the pessimistic hand, NP-completeness suggests that these problems do not have efficient algorithms; if proving otherwise amounts to conquering just a single problem, then why hasn't anybody succeeded yet? Most experts lean toward the latter interpretation and suspect that NP-complete problems don't have fast algorithms.

Whether the glass is viewed as half full or half empty, the concept of complete problems has changed the way researchers view computation. Karp showed that he could use an algorithm for one NP-complete problem to solve another by first demonstrating that you can translate seemingly unrelated problems into one another's language by using a process called a reduction. It works by showing you how to take any instance of one problem and convert it into another problem. For instance, if you start with a problem that involves a list of cities, flights between them and a budget, you can reduce it to a large Sudoku puzzle in such a way that the Sudoku has a valid solution only if it's possible to visit all the cities while staying within the budget (and doesn't have a valid solution otherwise). That way, if you discovered an efficient algorithm for

Sudoku, then you could use it to also solve the traveling salesperson problem by converting instances of the latter into Sudoku puzzles.

How Does Reduction Work?

For a deeper dive into how reduction works, let's reduce another type of NP-complete problem, the "map three-coloring problem," to the "clique problem." The map three-coloring problem asks: Given a map, can you assign one of three colors to each region so that no neighboring regions have the same color? And the clique problem asks: Does a given social network contain a group of a desired number of people who are all mutual friends? Both problems are NP-complete, meaning we don't know any efficient algorithm for either of them. On the surface, they have little in common. But I'll show that given a map, we can transform it into a social network in such a way that the answer to the social network problem will give us the answer to the map problem.

Picture a U.S. map. To build a social network out of it, designate three "people" for every state, one for each of three colors: blue, green and red. Then make two people friends unless:

1. They represent the same state (the green Wisconsin representative will not be friends with the blue Wisconsin one) *or*

2. They have the same color and represent neighboring states (North Dakota and South Dakota share a border, so their red representatives will not be friends, but North Dakota and Florida don't, so their red representatives will be friends).

I claim that this social network of 150 people will contain a clique of 50 mutual friends only if the U.S. map has a valid three-coloring. If we find 50 mutual friends in the network, they must all represent different states because in our design we didn't make people friends when they represented the same state. Furthermore, the coloring that corresponds to the clique would never result in neighboring states having the same color—we explicitly forbade such links in the network. So a clique of 50 people would correspond to a valid three-coloring. Likewise, if no 50-clique exists in the network, then no three-coloring exists for the map.

We just reduced the map three-coloring problem to the clique problem. This means if somebody discovered a fast algorithm for the clique problem, they could use it to solve any instance of the map three-coloring problem. Critically, the first step—transforming the map into a network—is fast. Creating the people in the network and the appropriate friendship relations does not require any exhaustive search or other infeasible computational overhead.

Reductions show that even if our problems seem one of a kind, they may be more universal than they appear. A web of reductions unites all NP-complete problems. Solve any one of them, and you can solve any other NP problem.

This ability to encode one problem by using the language of another is also a feature of computation itself. The implications boggle the mind. Remember we can frame proving mathematical theorems as an NP-complete problem. Pick any famous unsolved math question. The theory of NP-completeness tells us that there exists some level of Candy Crush that perfectly encodes that question. If a certain score is achievable in a certain number of moves on that level of Candy Crush, then your math problem has a proof of a certain length; otherwise it doesn’t. NP-completeness also assures us that certain advances in protein folding (or box packing or Sudoku solving) would destroy the digital economy. That’s because the encryption that protects our sensitive data works by vaulting them behind computational problems believed to be intractable.

It’s worth noting that although solving an NP-complete problem would allow you to break encryption, the reverse is not true; the intractable problems underlying most encryption schemes are not quite NP-complete themselves.

With so much riding on NP-complete problems, a million bucks might seem like a bargain for their solution. And it might offer a bit of added motivation the next time you struggle to schedule your vacation trip or crack a Sudoku puzzle.

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 him on X @JackPMurtagh

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https://www.scientificamerican.com/article/the-math-mystery-that-connects-sudoku-flight-schedules-and-protein-folding

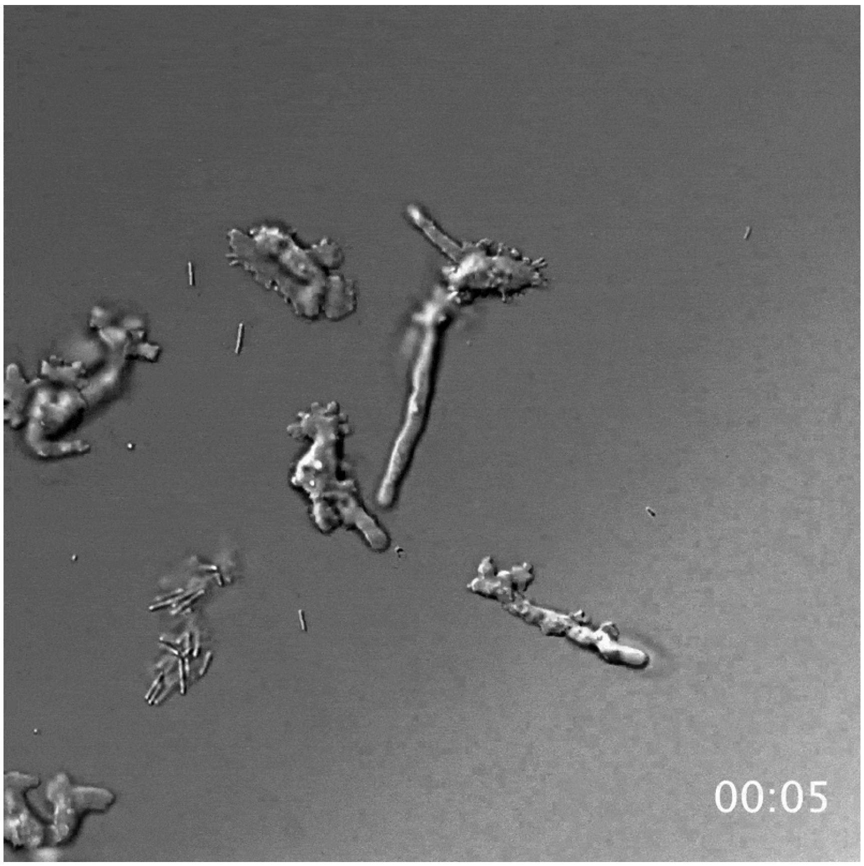
Microbiology

- **Extremophile ‘fire amoeba’ pushes the boundaries of complex life**
  It was thought that complex cells couldn’t survive above a certain temperature, but a tiny amoeba has proven that assumption wrong

Newly discovered ‘fire amoeba’ pushes the boundaries of life on Earth

It was thought that complex cells couldn’t survive above a certain temperature, but a tiny amoeba has proven that assumption wrong

By Andrea Thompson edited by Sarah Lewin Frasier



Incendiamoeba cascadensis (meaning “fire amoeba ... from the Cascades,” according to a recent preprint paper) is seen moving around in a zoomed-in microscopic view.
“A Geothermal Amoeba Sets a New Upper Temperature Limit for Eukaryotes,” by H. Beryl Rappaport et al. Preprint posted to bioRxiv on November 24, 2025 (CC BY-NC-ND 4.0)

A tiny amoeba has broken a pretty big record.

The newly discovered species of single-celled organism can divide and reproduce at a piping hot 63 degrees Celsius (145 degrees Fahrenheit), a higher temperature than possible for any other known complex form of life. The discovery, described in a preprint study on the server bioRxiv and not yet peer-reviewed, “pushes the boundaries of our understanding of life’s limits on Earth and the implications for life beyond Earth—where else and how else life might be able to take hold and thrive,” says microbial ecologist and astrobiologist Luke McKay, who was not involved with the study.

Much of the existing research into extremophiles—life-forms that thrive at extreme temperatures, acidity levels, or other environmental conditions—has concentrated on bacteria and archaea that lack a nucleus or membrane-bound cell organelles. The record-holding organism for withstanding high temperature is an archaean, *Methanopyrus kandleri*, which can grow at temperatures of 122 degrees C. The most heat-loving bacteria, *Geothermobacterium ferrireducens*, can grow at temperatures up to 100 degrees C.

But conventional wisdom since the early 1970s had been that eukaryotes—organisms with a cell nucleus, from amoebas to animals—would not be able to cope with high temperatures as readily because of their more complex biology. High temperatures can, for example, cause proteins necessary for life to fall apart. Before now, eukaryotes had been shown to tolerate temperatures up to only about 60 degrees C, and scientists typically assumed they could tolerate nothing higher than 62 degrees C.

Lassen Volcanic National Park.

John Elk/Getty Images

To explore the world of eukaryote extremophiles, microbiologists Angela Oliverio and Beryl Rappaport, both at Syracuse University, and some of their colleagues took samples from Lassen Volcanic National Park, in the Cascade mountain range in northern California, and cultured them in flasks back in their laboratory. Within a few weeks of sample growth, researchers spotted the never-before-seen amoeba species in flasks that had been kept at temperatures similar to those of the stream it was found in. As the researchers notched up the temperature, the amoeba, dubbed *Incendiamoeba cascadensis* (meaning “fire amoeba from the Cascades,” according to the preprint), kept on going. It was able to replicate itself in temperatures of up to 63 degrees C, remain active at up to 64 degrees C, and form a protective coating and survive encased in it at up to 70 degrees C, reawakening when the temperature was lowered again. “Our minds were kind of blown at that point,” Oliverio says.

The researchers also sequenced the amoeba’s genome and looked at its proteome, the proteins its genes are predicted to produce. Their findings suggest its go-to proteins have a higher average melting temperature than those of its nearest amoeba relative.

“The difference between 60 and 63 degrees C may sound small but represents a relatively large shift in our current understanding of eukaryotic limits,” says McKay, who works at biotechnology research company Symbiotic Biosystems.

“A Geothermal Amoeba Sets a New Upper Temperature Limit for Eukaryotes,” by H. Beryl Rappaport et al. Preprint posted to bioRxiv on November 24, 2025 (CC BY-NC-ND 4.0); Aerial Filmworks/Getty Images

The new finding has implications beyond just biology: for instance, understanding how such organisms survive high heat can help researchers develop heat-tolerant proteins and enzymes for other applications. “Why would I care about an amoeba in a random national park?” Oliverio says. “Well, your laundry detergent might be improved.”

But she dwells more on the existential implications: “It raises a lot of interesting questions about what are the constraints” on life, Oliverio says. “And we have really no idea. We sampled the stream and got this amoeba from one geothermal area. There could be hotter things out there. There probably are.”

Andrea Thompson is senior desk editor for life science at *Scientific American*, covering the environment, energy and earth sciences. She has been covering these issues for nearly two decades. Prior to joining *Scientific American*, she was a senior writer covering climate science at *Climate Central* and a reporter and editor at *Live Science*, where she primarily covered earth science and the environment. She has moderated panels, including as part of the United Nations Sustainable Development Media Zone, and appeared in radio and television interviews on major networks. She holds a graduate degree in science, health and environmental reporting from New York University, as well as a B.S. and an M.S. in atmospheric chemistry from the Georgia Institute of Technology. Follow Thompson on Bluesky @andreatweather.bsky.social

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https://www.scientificamerican.com/article/extremophile-fire-amoeba-pushes-the-boundaries-of-complex-life

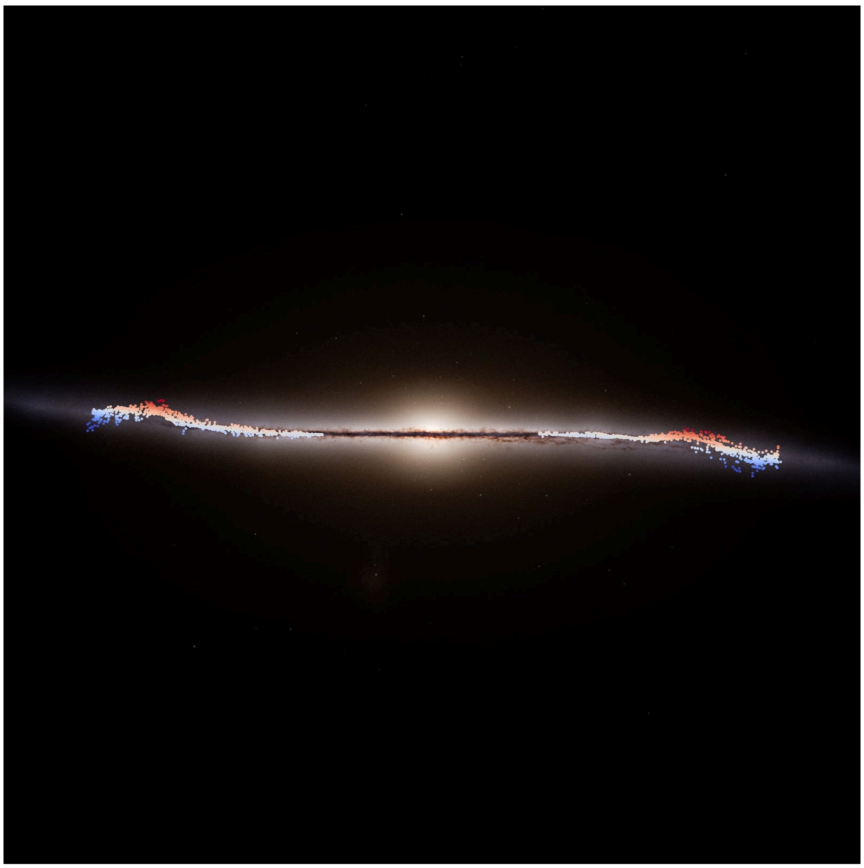
Milky Way

- **Why is the Milky Way warped?**
  Observations show the disk of our galaxy is not flat but warped and waving. Astronomers are still working out the reasons why

Our Milky Way's warped disk keeps getting weirder

Observations show the disk of our galaxy is not flat but warped and waving. Astronomers are still working out the reasons why

By Phil Plait edited by Lee Billings & Clara Moskowitz



Observations from the European Space Agency's Gaia mission have revealed a giant wave rippling through the disk of the Milky Way. This image, derived from Gaia data, shows an edge-on view of our galaxy; the data points for the newfound wave are plotted in red (*above the disk*) and blue (*below the disk*).
ESA/Gaia/DPAC, S. Payne-Wardenaar, E. Poggio et al. (2025)

Well, it's confession time: I've been lying to you.

I've said on many occasions in this column that our Milky Way galaxy has a flat disk. But it's not really flat—not according to any reasonable definition of the term, at least.

Now, in my defense, I wasn't exactly prevaricating; I was *simplifying*. That's a perfectly acceptable and even advantageous thing to do in science. When you're trying to understand or explain some complex thing, it helps to make it as simple as possible so that the math and physics are easier to crack. It's like assuming, at first, that Earth is a perfect sphere or that the sun contains all the mass in the solar system. Once you work out the basic equations that describe your simplified model, you can gradually add complexity back in—but in a way that makes the problem tractable.

To be fair, when you look at the glow of the Milky Way from a dark site, it does look flat—flat-*ish*. And lots of similar galaxies and their disks also appear flat.

But many of them, maybe even most of them, aren't. They're wiggly and wavy and bendy. Our galaxy is part of this warped group.

First, a quick overview: The Milky Way is classified as a disk galaxy, with a broad, circular collection of stars, gas and dust about 120,000 light-years across. It's a few thousand light-years thick, so "flat" is at least a decent adjective to use for it. In its center is a bulge of stars, and the entire thing is surrounded by a vast halo of stars and dark matter about a million light-years wide.

That last bit is important. Hang on a minute, and I'll explain why.

We've known for some time that out toward its edges, the disk of the Milky Way is warped—flared up on one side and down on the other rather like the brim of a fedora. Research published in the journal *Science* in 2019, however, refined this idea considerably. The team of astronomers behind that paper used data from Gaia, a now retired European Space Agency mission that mapped the positions, motions and distances of more than a billion stars. They specifically looked at Gaia's observations of some 2,400 Cepheid variables—special kinds of stars that pulsate, changing in brightness. The time it takes for a Cepheid’s brightness to change is related to its luminosity, the amount of energy it gives off. By comparing a Cepheid’s intrinsic luminosity with how bright the star appears in our sky, we can calculate its distance.

By mapping so many Cepheids in the galactic plane, the scientists were able to trace the overall shape of the Milky Way’s disk, and they found that the warping really stands out. Our galaxy looks a bit like a vinyl LP that’s been out in the sun too long (kids, ask your grandparents).

What causes such warping? It’s possible for a collision with a smaller galaxy to gravitationally affect the stars in a disk, similar to the way a rock tossed into a pond creates spreading ripples. But astronomers who presented their research in *Nature Astronomy* in 2023 had a very different idea for what’s been tugging on our galaxy’s brim: dark matter.

As I mentioned earlier, the galaxy is embedded in a halo of stars and dark matter. About a year before publishing their paper, some of the members of this team, along with other astronomers, found that the stellar halo was not spherical, as previously assumed, but instead was elongated and squished a little like a slightly flattened American football. It was also tilted with respect to the plane of the galaxy.

They posited that the more diffuse and nigh-invisible dark matter halo might have the same shape as the stellar halo. By modeling the effects that the much more massive dark matter halo would have if it were structured and oriented in a similar way, they found that this formation naturally created a gravitational field that tugged on the disk, which would explain not just the shape and size of the warp but also its orientation in the disk. Although this isn’t necessarily case closed, they do make a pretty solid argument.

But that's not the only way our galaxy's disk is off-kilter. New research shows it's also corrugated.

Last year another group of scientists used Gaia data to look at 17,000 young stars—which tend to form right in the middle of the galaxy's disk—and 3,400 Cepheid variables in a region of the Milky Way tens of thousands of light-years across. They found that in the main disk and well into the warped outer parts, there is an up-and-down wave that strongly resembles the corrugation pattern in thick cardboard.

It's similar to the "wave" fans do at sports games, where they stand up and sit back down in a swell that moves around the stadium. In the Milky Way's case, the stars in the galaxy move up and down relative to the plane of the disk. Because so many of the stars the researchers measured are young, the scientists think the gas in the galaxy—which forms stars—moves up and down as well. So whatever this pattern is, it's intrinsic to the structure of the disk.

The cause of this wave isn't known, but the most likely culprit is, this time, a collision with a smaller galaxy. One potential, even probable, guilty party is the Sagittarius Dwarf Spheroidal galaxy, a small object with a tiny fraction of the Milky Way's mass. It orbits our galaxy in a nearly vertical loop, diving through the disk as it goes. In 2018 astronomers published a paper in *Nature* reporting that they had found—again, using Gaia data—wavelike motions in six million stars within approximately 10,000 light-years of the sun, similar to the waves found in the outer disk. They suggest that the Sagittarius galaxy might have created these structures the last time it passed through the disk, several hundred million years ago.

The sun also displays this motion; careful measurements show it has a vertical velocity as it orbits the galactic center. Our solar system bobs up and down with it. Every so often it moves through the disk, but after it reaches some distance from it, the gravity of the disk pulls it back, and the cycle starts again. This element of our star's motion may be a part of that greater wave.

So, as you can see, I wasn't really lying before about our flat disk. I was simply eliding over details that aren't necessary in a discussion of the overall structure of the galaxy. Yet it's certainly worth looking at these extra effects—they tell us about the history of our Milky Way and can even reveal how the sun plays its part as well.

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https://www.scientificamerican.com/article/why-is-the-milky-way-warped

Neuroscience

- **The neuroscience behind the ‘parenting paradox’ of happiness**
  Separate brain processes cope with moment-to-moment versus big-picture experiences, which helps to explain how parenting both increases and decreases aspects of well-being

The neuroscience behind the ‘parenting paradox’ of happiness

Separate brain processes cope with moment-to-moment versus big-picture experiences, which helps to explain how parenting both increases and decreases aspects of well-being

By Anthony Vaccaro edited by Daisy Yuhas & Allison Parshall

Dusan Stankovic/Getty Images

Whether to have kids can be one of the most momentous decisions a person makes. Countless factors can sway this choice. How will it affect your finances, your relationships or your career? Are you feeling pressure from your family or community? But one of the simplest, most personal considerations is whether, and how, having a child will affect your quality of life.

Here psychologists studying well-being have encountered what’s sometimes called the “parenting paradox”: parents report lower mood and more stress and depression in their daily lives than adults without children, and yet parents also tend to report greater life satisfaction in general. How do we make sense of this contradiction?

My colleagues and I have conducted research that can help us answer that question—and, along the way, highlight the complexity of what makes for a good life. I'm an emotion neuroscientist by training, and I want to use brain science to understand the messy and complicated feelings people experience in modern times. Feelings such as bittersweetness in reminiscences about an ex, simultaneous excitement and fear before a performance, or ambivalence about a big life change are not easily quantified with the positive-negative scales scientists use in research—still, they can tell us a lot about how we process emotion when it matters the most.

During my postdoctoral training, I worked at the University of Southern California in a laboratory focused on the parenting brain. That team has been following a group of first-time fathers through their partners' pregnancy and their development as parents. I realized that studying these new dads over time would give me a chance to investigate how parenting relates to a meaningful life and what occurs in the brain as people's lives change.

Focusing on "meaning in life" allowed me to study an aspect of well-being that transcends daily stressors—because parenthood is famously stressful. Unfortunately, I cannot tell you what the meaning of life is, but in psychology it's measured according to people's subjective reports about whether their life is coherent and has an overarching purpose. This abstract feeling that "things make sense" has been shown to be a powerful predictor of overall well-being and mental health, even when people are going through objectively difficult times. Research has shown that individuals who perceive greater meaning in life are often more resilient against bigger mental health problems that might arise from adverse events such as global pandemics, severe disease and war trauma.

In our study of 88 new fathers, my colleagues and I predicted that about six months after the birth of their first child, most of them would report an increase in meaning compared with their reports during their partner's pregnancy. Instead we found a roughly even split between participants experiencing an increased or decreased sense of meaning. Clearly, only about half of the fathers felt that life was more purposeful because they had become a parent. But that was just the first of several important insights.

> Whether parenthood makes people happier has less to do with the children (sorry, kids) and more to do with long-term goals.

Of our participants, 35 agreed to undergo a form of brain imaging called functional magnetic resonance imaging (fMRI) both before and after the birth of their child. We used these brain scans to calculate how in sync each part of the brain was with the others. For people with strong functional connectivity, when activity increases in one area, it also ramps up in the rest of the brain. Other scientists have conducted fMRI studies with hundreds of people and found that this measure is related to increased meaning in life, potentially because greater connectivity in the temporal lobe and other emotion-related regions of the brain allows for better integration of emotional, self-oriented and abstract thinking.

We wondered whether this connectivity changes during a major life event such as having a child and, if so, whether this change is related to one's sense of meaning and purpose. By comparing scans before and after our participants became fathers and reviewing their reports about their experiences, we modeled whether functional changes in different parts of someone's brain predicted either their sense of meaning in life or their (positive or negative) feelings about parenting.

People with positive parenting feelings exhibited more connectivity changes in parts of the brain that are important for self-control (the middle frontal gyrus) and empathy (the supramarginal gyrus).

Those with more negative parenting feelings showed changes in the sensory cortex and cerebellum, which may relate to hyperemotional sensitivity to sensory information. (If a baby's cry always triggers a hyperstressful response, parenting is going to be very difficult.) In fathers whose sense of meaning stayed the same or increased, we noted more brain connectivity in regions such as the insular cortex and the temporal pole. These areas are crucial for integrating a person's emotions and senses with their broader sense of identity, suggesting that fathers who more effectively engage in this contextualizing process during this new life stage tend to flourish.

With these differences, we can start to think more deeply about the parenting paradox. A father might feel overwhelmed by sleepless nights yet still contextualize this experience as part of a meaningful existence. In other words, the challenging emotions people deal with in the short term can become independent from a long-term sense of satisfaction, potentially because separate brain processes underlie the two feelings. Without this cognitive translation, day-to-day stressors may dictate a person's overall sense of well-being, or the mix of and shifts between positive and negative parts of parenting may make life seem incoherent overall. Integrative regions such as the temporal poles and insular cortex allow both positive and negative events to fit together, potentially into a framework that facilitates long-term well-being.

This distinction fits into a larger body of research about how people build what scientists call a "coherent self-narrative," or the story individuals tell about themselves. For example, past research has found that simply viewing oneself as being on a "hero's journey" increases resilience. When someone can situate their feelings in a story that makes sense to them, it may not matter whether a particular situation is positive or negative as long as it fits into their longer-term goals. It seems that whether parenthood makes people happier therefore has less to do with the children (sorry, kids) and more to do with whether that goal of parenthood aligns with the individual's thinking.

A recent analysis of data collected from German adults between 1984 and 2021 actually found no average difference in the well-being of middle-aged adults with children versus those without, although there was more variability for parents than there was for nonparents. What was really interesting, however, was the results for young adults. The most important factor for understanding these people's well-being was not whether they had kids but the importance they placed on the goal of having kids. Childless young adults who placed high importance on becoming parents experienced lower life satisfaction as they grew older—*if* their perceived importance of this goal remained high as they aged.

But those people were a minority. Most of those child-free adults deemphasized that goal as they aged, and their happiness rating was then no different from that of adults with kids. This finding might highlight the takeaway for our study's dads and for those questioning whether they want children: meaning can be created regardless of the choice made. Our adaptive brain can shift journeys, reimagine stories and help us thrive even when life throws us a curveball—or a screaming infant at two in the morning.

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* dyuhas@sciam.com.

Anthony Vaccaro is a research assistant professor at the University of North Carolina at Chapel Hill. He studies the neuroscience of emotion in modern contexts.

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https://www.scientificamerican.com/article/the-neuroscience-behind-the-parenting-paradox-of-happiness

Paleontology

- **This fossil is rewriting the story of how plants spread across the planet**
  An enigmatic group of fossil organisms has finally been identified—and is changing the story of how plants took root on land

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This fossil is rewriting the story of how plants spread across the planet

An enigmatic group of fossil organisms has finally been identified—and is changing the story of how plants took root on land

By Taylor Mitchell Brown edited by Andrea Thompson & Sarah Lewin Frasier

Artistic reconstruction of *Spongiophyton* during the Early Devonian in the Paraná Basin in present-day Brazil.
J. Lacerda/Bruno Becker-Kerber et al., "The rise of lichens during the colonization of terrestrial environments," in *Science Advances*, Vol. 11, No. 44; October 29, 2025

Around 410 million years ago terrestrial life was relatively simple. There were no forests or prairies—land was largely dominated by slimy microbial mats. The types of plants that would eventually give rise to trees and flowers had only just evolved and would take another several million years to fully flourish and diversify.

A new discovery is rewriting the story of how these vascular plants, as they are called, spread onto land. Researchers might have finally resolved a debate about the pervasive but enigmatic fossil organism called *Spongiophyton*: it seems to have been an unusual life-form called a lichen that could have helped pave the way for land plants to thrive.

Fragment isolated from the stem of *Spongiophyton nanum* showing its upper surface with pores.
Bruno Becker-Kerber et al., “The rise of lichens during the colonization of terrestrial environments,” in *Science Advances*, Vol. 11, No. 44; October 29, 2025

The discovery, published recently in *Science Advances*, “settles a question that had been open for more than a century,” says paleontologist Geovane Gaia of the Institute of Geosciences at the State University of Campinas in Brazil, who was not involved with the research. Rather than appearing only after vascular plants, as most assumed, lichens “were already there at the beginning, literally helping prepare the ground for plant life.”

Lichens are the symbiotic result of fungi and photosynthetic algae or cyanobacteria working together. Today that amalgam helps to churn lifeless rocks and sediments into nutrient-rich soil everywhere from polar deserts to tropical forests, says study lead author Bruno Becker-Kerber, a paleontologist at Harvard University. Vascular plants have tissues that funnel those soil nutrients from the ground to their stems and leaves.

Because lichens’ soft body tissues are rarely preserved in the fossil record, their origins have remained mysterious. A 2019 genetic analysis suggested they evolved well after the emergence of vascular plants, indicating they probably played little to no role in early land colonization.

But scientists have long debated whether *Spongiophyton*, which flourished at least 410 million years ago, was actually a lichen rather than an alga. To determine its identity, Becker-Kerber and his colleagues analyzed the underlying chemical properties of lingering organic material within the fossils.

Lichens contain fungi whose cell walls are lined with chitin, the same material that makes up insect exoskeletons. Chitin is loaded with nitrogen, and the team's results turned up an unmistakable nitrogen signal. "The more we tested it, the more consistent the signal became," Becker-Kerber says. "It was genuinely exciting."

There were other fungal traits present, too, such as a distinct branching pattern exhibited by growing fungal cells called hyphae. The results suggest lichens evolved at least 410 million years ago, shortly after the initial spread of vascular plants around 420 million years ago but before the earliest known forests around 390 million years ago.

"If *Spongiophyton* was a lichen, it may have enabled the expansion of land plants into areas previously uncolonized," says Matthew Nelsen, an evolutionary biologist at the Field Museum of Natural History in Chicago, who was not involved with the research.

Becker-Kerber adds that "it's a major shift in how we view the complexity of life's first steps onto land. [*Spongiophyton*] likely weathered rocks, stabilized sediments, cycled nutrients and contributed to the formation of protosoils just before forests developed."

The emergence of lichens near the beginning of terrestrial plants' spread suggests a new page in Earth's early history. "People often tell the story of life's move onto land as a 'plant story,'" Becker-Kerber says. "What our study shows is that fungi and lichens were also part of it."

Taylor Mitchell Brown is a San Diego–based journalist covering anthropology and paleontology, with occasional forays into other disciplines. You can find him in *Science*, *Science News*, *New Scientist*, *National Geographic*, *Scientific American* and elsewhere. Read his latest musings on Bluesky @tmitchellbrown.bsky.social

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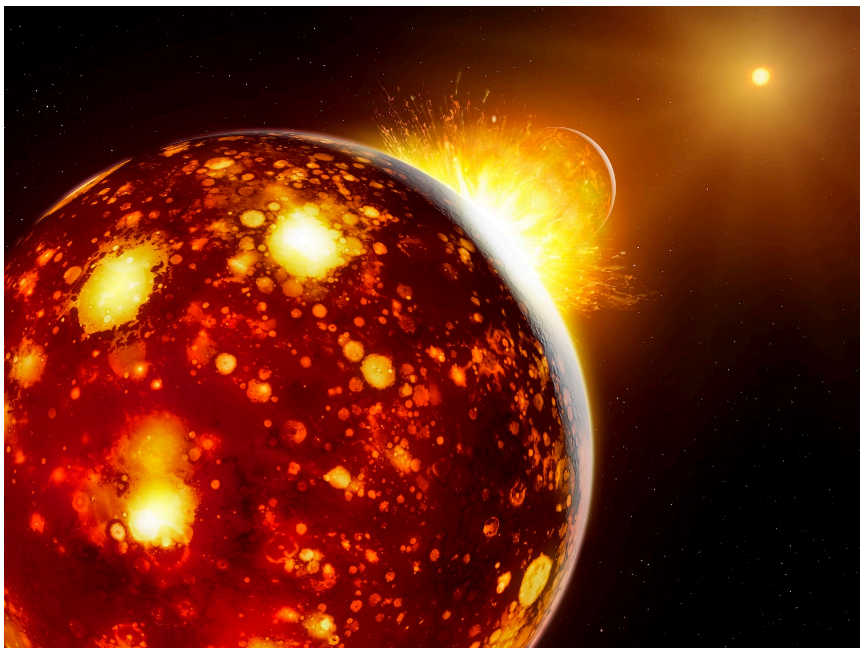
Planetary Science

- **Lost planet Theia, which created the moon, came from the inner solar system**
  New work pinpoints the origins of the planet Theia, whose ancient collision with Earth likely produced the moon

The lost planet that created the moon came from the inner solar system

New work pinpoints the origins of the planet Theia, whose ancient collision with Earth likely produced the moon

By Jacek Krywko edited by Sarah Lewin Frasier



Artist’s impression of the planet Theia colliding with ancient Earth to create the moon.
MPS/Mark A. Garlick

Roughly four and a half billion years ago the planet Theia slammed into Earth, destroying itself, melting large portions of our planet’s mantle and ejecting a huge debris disk that later pulled together to become the moon. Scientists have long wondered about both the composition and the origin of Theia. Now they have evidence that it formed very close to home.

The original giant-impact model of the moon’s formation, proposed in the 1970s, predicted that the moon was made mostly of material from the colliding object. This scenario implied there should be differences between the chemical compositions of the moon and

Earth, but research has found that the two are nearly identical—far more similar than two independent planetary bodies should be. A study published recently in *Science* took a close look at other things Theia gave us besides the moon: additional molybdenum and iron left behind on Earth from the collision.

Ancient Earth would have accumulated these heavy elements in its core but not in the rocky mantle closer to the surface, so any iron present now in Earth's mantle most likely came from Theia. Thus, it can tell us about that planet's composition, says study co-author Thorsten Kleine, director of the planetary science department of the Max Planck Institute for Solar System Research in Germany.

Kleine and his colleagues analyzed 15 terrestrial rocks and six lunar samples brought to Earth by Apollo missions. They focused first on iron isotopes: variations of the element with different numbers of neutrons. Rocks and planets in the solar system share nearly identical distributions of these isotopes, but in the past few years Kleine and some of his co-authors discovered that certain tiny deviations from the standard iron isotope ratio can reveal the sample's place of origin. "The discovery of iron isotope anomalies is relatively recent, which I guess is why no one has done it for the moon so far," Kleine says. "These analyses are difficult, and the variations are small, so it is not an easy experiment to do." The team combined the data on iron with isotope distributions of molybdenum and zirconium found in the same samples to reverse engineer Theia's likely size and composition. The researchers also compared the measurements with those of samples from 20 meteorites, some of which originated in the inner solar system and some in the outer, to determine Theia's place of origin.

The new study reveals Theia as a rocky planet with a metallic core that most likely had a mass 5 to 10 percent of Earth's and that formed in the inner solar system, closer than Earth to the sun. This picture lines up with previous hypotheses for why the bodies seemed to have so much in common, Kleine says; what we didn't know was exactly where Theia originated.

Back in 2020 Kleine and other scientists demonstrated that celestial bodies that formed closer to the sun are richer in heavy elements. Following this principle, Kleine and his co-authors estimated that Earth has a bit more molybdenum and zirconium than it should, and they figured these additional heavy elements must have been brought here by Theia. They combined those data with what they had learned about the iron.

Planetary scientist Sara Russell, a senior research lead at the Natural History Museum, London, who was not involved in the new findings, praises the exceptional precision of the authors' iron measurements. For her, the study's implications go beyond just the origins of Theia—they offer insights into the conditions that eventually shaped the Earth-moon system into a cradle of life. "This careful work and insightful modeling help us better understand our origins," she says.

The team hasn't yet run simulations of the giant impact based on this proposed scenario, Kleine says, but he looks forward to doing so and to analyzing lunar samples to look for other element isotopes.

Russell hopes future sample-return missions can boost this type of analysis. "I find it amazing we are still learning new things about the moon and Earth more than 50 years since the Apollo astronauts collected these rocks from the lunar surface," Russell says. "Collecting samples in space and bringing them to curate on Earth means we can make much more detailed measurements than are possible in space and preserve them for future generations to make their own discoveries."

Jacek Krywko is a freelance writer who covers space exploration, artificial intelligence, computer science and all sorts of engineering wizardry.

https://www.scientificamerican.com/article/lost-planet-theia-that-created-the-moon-came-from-the-inner-solar-system

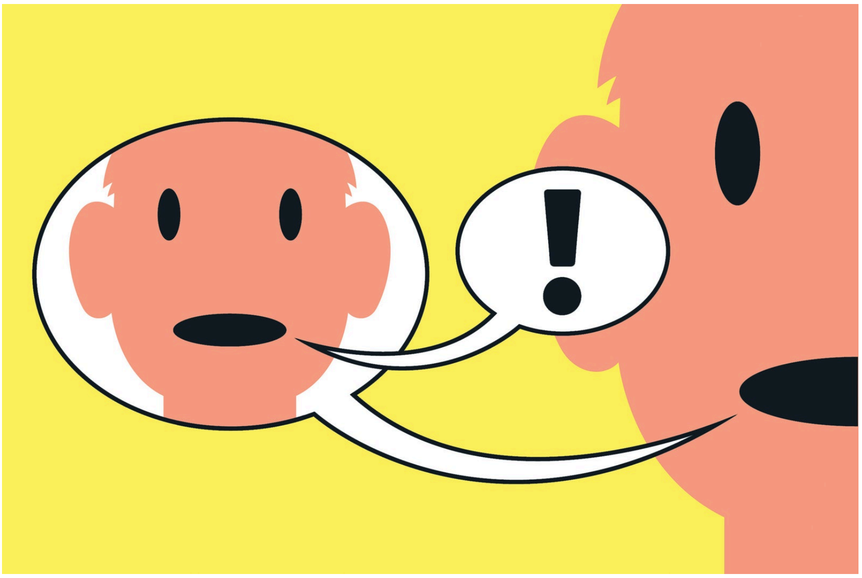
Schizophrenia

- ## Not everyone with schizophrenia hears voices. Here’s why
  New research aims to tease out what exactly is happening in the brains of people with schizophrenia who have auditory hallucinations

Why do only some people with schizophrenia hear voices?

New research aims to tease out what exactly is happening in the brains of people with schizophrenia who have auditory hallucinations

By Hannah Seo edited by Lauren J. Young & Sarah Lewin Frasier



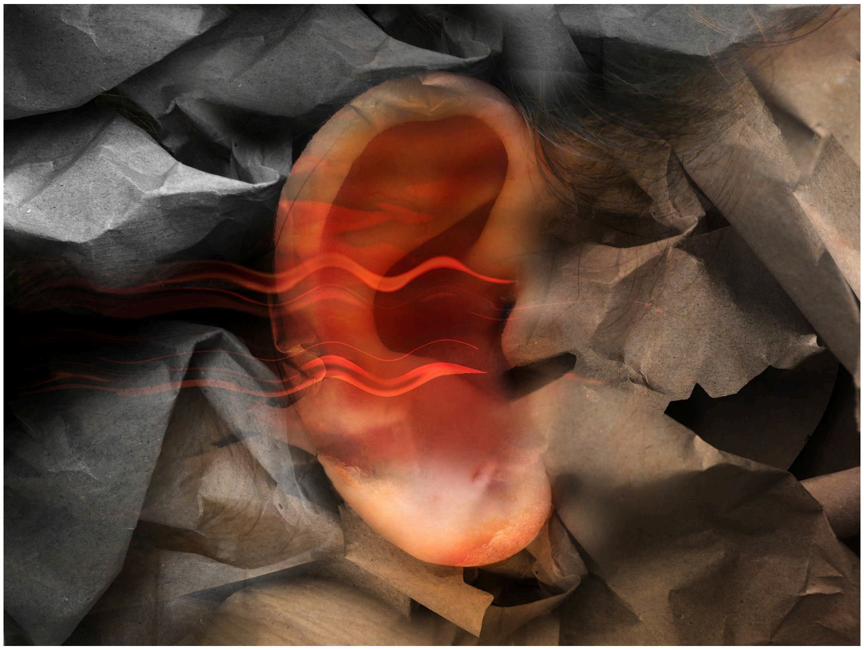
Thomas Fuchs

Hearing imaginary voices is a common but mysterious feature of schizophrenia spectrum disorders. Up to 80 percent of people with these conditions experience auditory hallucinations, hearing speech or other sounds when there are none. Now research has gotten us closer to unraveling the brain mechanisms behind this phenomenon.

Experts have long thought auditory hallucinations arise from a person's perception of their inner thoughts as real voices coming from the outside world. When people without schizophrenia speak or prepare to speak, the brain region that plans movements suppresses signals in the auditory cortex, the part of the brain that processes sound. This action helps people distinguish their own speech from external noise. Researchers theorized this mechanism could apply to healthy people's inner speech as well—although that has been difficult to study and verify. Dysfunction in the activity between these brain regions might lead to hearing voices.

In a study published in *Schizophrenia Bulletin*, researchers demonstrated that inner speech indeed suppressed the brain's auditory cortex in adults without schizophrenia. But in people with the condition who experienced auditory hallucinations, they found, inner speech boosted the auditory cortex's response.

"The hard thing with studying inner speech is that it's inherently private," says Thomas Whitford, a cognitive neuroscientist at the University of New South Wales in Australia and co-lead author of the study. To eavesdrop on that inner speech, Whitford and his colleagues used electroencephalography (EEG) to measure brain activity in individuals with conditions on the schizophrenia spectrum, including participants who heard voices and those who did not (but might have in the past), and in those who didn't have such conditions. The researchers prompted the participants to imagine saying a specific syllable, either "bah" or "bee," without actually moving their mouth. At the same time, a sound played through the subjects' headphones that either matched or mismatched the sound they were told to imagine speaking. As a control condition, participants were sometimes told not to imagine anything and to simply listen to the sounds with their headphones.



anand purohit/Getty Images

In adults without schizophrenia, simultaneously hearing and mentally producing a sound dampened the auditory cortex's response compared with brain activity when they only listened without thinking of saying anything. The effect was strongest when the sound they heard matched the one they imagined. But participants with schizophrenia who had auditory hallucinations experienced the opposite effect: when the two sounds matched, their brain response was even stronger. People with schizophrenia who did not currently hear voices showed strong dampening in the auditory cortex with mismatched sounds but no dampening when the sounds matched. Whitford suggests this finding may be a sign that these participants had the potential to hallucinate.

This paper builds on previous research by neuroscientist Xing Tian of New York University Shanghai and his colleagues. Tian's team has conducted numerous studies teasing apart mechanisms in the brain's motor and auditory regions, including mapping abnormal signals that could lead to confusion between inner and external sounds in people with schizophrenia.

Whitford and his colleagues' new study helps to clarify one possible mechanism for schizophrenia's auditory hallucinations, says Albert Powers, a psychiatrist at the Yale School of Medicine, who wasn't involved in the work. But further investigation is needed to see whether this pattern of brain activity contributes to all the different sound-based hallucinations people with schizophrenia might experience, he says, and not just voices.

Nevertheless, according to Mahesh Menon, a psychologist and co-head of the Schizophrenia Program at the University of British Columbia, who also wasn't involved in the study, this research is "quite clever," especially because these internal mechanisms are difficult to test experimentally. Menon adds that the new findings could be valuable for understanding how similar psychotic symptoms occur.

Powers emphasizes that experiencing auditory hallucinations doesn't always indicate severe schizophrenia and that a person with severe schizophrenia won't necessarily experience hallucinations. Disentangling the various pathways in the brain that could drive these hallucinations may lead to new treatment options, and "this paper helps to get us there," he says. Whitford hopes his team's EEG test could eventually be used to assess someone's risk of developing psychotic symptoms and hallucinations. That predictive ability, he says, would be the "holy grail" that could help direct people toward early preventive treatment.

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Science in Images

- **Why does life keep evolving these geometric patterns?**
  A global catalog shows how creatures across the tree of life balance rigidity with flexibility in remarkably consistent ways

Why does life keep evolving these geometric patterns?

A global catalog shows how creatures across the tree of life balance rigidity with flexibility in remarkably consistent ways

By Anirban Mukhopadhyay edited by Sarah Lewin Frasier

The same tile structures with soft joints between are found across the tree of life, including on mirror spiders' abdomens.
Manoj Kumar Tuteja/Getty Images

The mirror spider can rapidly shift a patchwork of minuscule reflective plates underneath its abdomen's outer surface, altering the pattern of mirrorlike flashes. This uncommon display comes from common building blocks: Similar tilelike arrangements of plates and soft joints appear throughout the tree of life, from turtle shells to tropical fruit peels. Researchers have now compiled 100 examples of this pattern across animals, plants, microbes and viruses, which they describe in *PNAS Nexus*.

Study co-author Mason Dean, a biologist at City University of Hong Kong, first noted a regular tiled pattern in micro computed tomography scans of a ray skeleton. He was surprised to find that what looked like pixelated graininess was actually a mosaic of tiny hexagons and pentagons packed edge to edge across the cartilage. Humboldt University of Berlin zoologist Jana Ciecierska-Holmes, also a co-author, began looking for tile examples and was similarly surprised to spot intricate interlocking plates on the outer coating of millet seeds. They and their colleagues set out to determine just how widespread such tiling patterns were.

Chitons’ shell plates and girdles.
Cavan Images/Alamy

The researchers focused on true tessellations, in which geometric tiles are discrete structural pieces separated by softer seams, rather than purely visual or hollow patterns such as animal coloration or honeycombs. To compare such systems across very different organisms, they created a framework describing what different natural tiles are made of, how they’re shaped, how they connect and what they do. The results reveal structural parallels across many organisms without any shared ancestry.

Salak fruit’s outer covering.
Picture Partners/Alamy (*top and bottom*)

Chitons evolved articulated shell plates, whereas sharks developed tessellated cartilage—two tiled structures that arose independently in distant evolutionary lineages, the researchers found—and microscopic amoebae build architecturally similar protective casings from scavenged mineral tiles. Other variants tile the lenses of insect eyes and form corky plate patterns in the elephant’s foot plant. Across kingdoms, the same basic layout helps animals see, move and protect their bodies.

Butterfly wing scales.
nevodka/Alamy

The recurrence reflects how geometry and growth push organisms toward the same solutions. Predominantly six-sided patterns such as those on sharks and rays are a classic way to efficiently cover curved surfaces, for instance. Dean also notes that tile borders often align with regions where new cells are added during growth, allowing tissues to function as they expand. Plus, pairing hard tiles and softer seams balances stiffness and flexibility, adds Kiel University zoologist Stanislav Gorb, who was not involved in the study. “Too rigid a structure is good for resisting forces but poor for generating motion.”

Armadillo lizards' bony plates.
Nature Picture Library/Alamy (*top*); Life on white/Alamy (*bottom*)

The authors hope their online catalog becomes a living resource to help people recognize these patterns in the organisms and structures they study. "Once you start paying attention to that, you see it everywhere," Dean says. Ciecierska-Holmes agrees: "You kind of go into the tessellation world."

Anirban Mukhopadhyay is an independent science journalist based in India. He has a Ph.D. in genetics from Delhi University and writes about science policy and cutting-edge biomedical research. Find him on X @onipedia and on LinkedIn.

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https://www.scientificamerican.com/article/why-does-life-keep-evolving-these-geometric-patterns