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Features

- **Miners Are Pulling Valuable Metals from the Seafloor, and Almost No One Knows about It**
  The owners of a controversial mining license have begun extracting valuable metals from the ocean floor
- **These Mysterious Shapes Are at the Heart of Math’s Biggest Puzzles**
  Mathematicians describe the most beautiful and beguiling forms and surfaces they know
- **A New Bee Crisis Could Make Your Food Scarce and Expensive**
  Scientists are racing to stop a tiny mite that could devastate the pollinators and agriculture
- **Hypochlorous Acid Is Trending in Skin Care and Cleaning—But Does It Work?**
  Hypochlorous acid is safe enough to spray in your eyes yet more effective than bleach. Why isn’t it everywhere?
- **Mysterious Dark Comets Could Unlock Solar System Secrets**
  A group of comets with unexplained movements presents a quandary
- **Male African Elephants Were Once Thought to Be Solitary—New Research Reveals They Have Complex Social Networks**
  Long thought to be loners, male African elephants turn out to have surprisingly rich social lives

Suddenly Miners Are Tearing Up the Seafloor for Critical Metals

The owners of a controversial mining license have begun extracting valuable metals from the ocean floor

By Willem Marx edited by Mark Fischetti

Mark Smith

In hindsight, I am still not sure why the operators of the Danish-flagged MV *Coco* allowed me onboard. By the time I arrived last June, the vessel had been sailing for several weeks in the Bismarck Sea, a part of Papua New Guinea's territorial waters, digging chunks of metal-rich deposits out of the ocean floor with a 12-ton hydraulic claw. The crew was testing the feasibility of mining seafloor deposits full of copper and some gold. It was probably the closest thing in the world to an operational deep-sea mining site. And the more I learned about the endeavor, the more surprised I became about the project's very existence.

On that summer morning, I arrived on a red catamaran after rolling over six-foot swells in the South Pacific for two hours, and I

clambered up a metal ladder hanging down on the *Coco*'s starboard side. The 270-foot, 4,000-ton vessel towers at its prow, its vast aft deck full of cranes, winches and a remotely operated submersible. I was there at the invitation of Richard Parkinson, who founded Magellan, a company that specializes in deep-sea operations. At the top of the ladder, two crew members hauled me onboard the ship, which was roughly 20 miles from the closest shore, and a British manager for Magellan named James Holt greeted me, his smile sun-creased from more than two decades at sea. After a safety briefing, he ushered me through a heavy door into a dark, windowless shipping container on the rear deck that served as a control room.

Inside the hushed cabin was a young Brazilian named Afhonso Perseguin, his face lit by screens displaying digital readings and colorful topographic charts. Gripping a joystick with his right hand, he delicately maneuvered a big, boxy remotely operated vehicle, or ROV, over a patch of seafloor a mile below. I watched on monitors as a robotic arm protruded from the ROV toward a monstrous set of clamshell jaws suspended from a cable that rose all the way up to the ship. Perseguin used the ROV's arm to steer the jaws as a colleague beside him radioed instructions to a winch operator on deck.

Hydraulics drove the open clamshell into a gray chunk of flat seafloor ringed by rocky mounds and jagged slopes. The opposing teeth dug in, throwing up clouds of silt that filled the video feeds from the ROV. The robotic arm released, and the winch started hauling the jaws, clamped shut around their rocky cargo, on an hour-long journey up to the ship.

Within minutes Perseguin reversed the ROV to survey the wider scene, revealing chimneys of rock looming up from the seafloor, pale yellow and gray in the submersible's powerful lights. Small mollusk shells dotted their surface; a crab scuttled out of frame. "Quite amazing, really, isn't it?" murmured John Matheson, a

shaven-headed Scot supervising the ROV team. As Perseguin steered the ROV slowly around a column, the cameras suddenly captured a glassy plume of unmistakably warmer water spewing up from a hidden crevice.

> Hydraulics drove the monstrous clamshell jaws into a gray chunk of seafloor, throwing up clouds of silt that filled the video feeds from the remotely operated vehicle.

That hydrothermal vent marked the edge of a tectonic plate in the Bismarck Sea. The metal-rich magma ejected over millennia from several such vents—some dormant, some still active like this one—was Magellan's prize. The teams on the ship, hired by a company called Deep Sea Mining Finance (DSMF), were conducting bulk seafloor mining tests under a 2011 mining license issued by the Papua New Guinea (PNG) mining regulator. I was the only reporter onboard to witness the operation.

Worldwide, oceanographers have found three distinct types of mineral deposits on the deep seafloor. Manganese crust is an inches-thick, metal-rich pavement that builds up over millions of years as dissolved metallic compounds in seawater gradually precipitate on certain seafloor regions. Polymetallic nodules are softball-size, metal-rich rocks strewn across enormous seafloor fields. And massive sulfide deposits, such as the ones being mined by the crew of the *Coco*, are big mounds and stacks of rock formed around hydrothermal vents. Over the past decade several companies have developed detailed but still hypothetical plans to profit from these deposits, hoping to help meet the world's surging demand for the valuable metals necessary for batteries, electric cars, electronics, and many other products. Scientists have warned that these efforts risk destroying unique deep-sea habitats that we do not yet fully understand, and governments have been reluctant to grant exploration licenses in their territorial waters. But from what I saw during my two days and one night onboard the *Coco*,

DSMF was digging in, and a new era of deep-sea mining had all but begun.

Holt, one of Magellan's offshore managers, said the aim was to test the physical requirements and environmental impacts of pulling up sulfide deposits. What would soon become unclear, however, was why the operators were stockpiling mounds of excavated rock on the seabed, and who in PNG knew the *Coco* was there.

I was back outside on the rear deck as the sun dipped below the horizon when the cables finally brought the locked clamshell with its heavy contents to the sea surface. The giant yellow jaws emerged from the waves, gleaming under the ship's floodlights. As they swung over the rear deck, water and small stones dripped from them; apparently the hydraulic system had failed to fully shut the contraption.

A handful of us stood watching as it opened, dumping the load with a loud thud onto a massive metal weighing tray. The scales showed that some of the anticipated material was missing, presumably dropped during the mile-long journey to the surface. Crew members who had already completed dozens of similar lifts said this loss was an unusual occurrence. But the failure highlighted just one of the dangers of underwater mining: clouds of sediment leaked during these hauls to the surface or kicked up when the seafloor is ripped apart could suffocate sea creatures or unintentionally disperse harmful minerals.

Mark Smith

The *Coco* had been bringing up a jaw-load roughly every 12 hours. Just before this latest cache was swung onboard, an Australian marine scientist named Josh Young had been preparing to drop his testing equipment over the ship's side. After each haul, he or his Papua New Guinean colleague Nicole Frani tried to measure the size and spread of the silt plume directly underneath the vessel. Using another winch, Young lowered a ring of long plastic cylinders known as Niskin tubes into the surf. Each sampling tube was set to open at a different depth as the ring passed down through the water column for several thousand feet. The scientists wanted to know how widely the cloud of silt "is spreading out and how it can affect the sea life below," Frani explained.

After less than an hour, Young hoisted the ring of tubes back up onto the deck. Peering over his shoulder, I watched an electronic screen reveal the water's temperature, acidity, salinity, density, cloudiness and oxygen content, as well as its oxidizing capacity and conductivity—proxies for water cleanliness—at each depth.

Like many offshore projects, the *Coco* operation was globalization incarnate. Frani and Young work for Erias, an Australian environmental consultancy that Magellan hired as a contractor for the summer's endeavor. Magellan also hired the South African and British deckhands helping Young, plus the ROV team and a number of Malaysian hydrographic surveyors. Itself headquartered in Guernsey, an island between the U.K. and France, Magellan had chartered the *Coco* from a Danish firm, with sailors from the North Atlantic's Faroe Islands and pursers from the Philippines. Much of the venture's financing—for daily costs topping tens of thousands of dollars over several months—came from Russian and Omani investors, who had registered DSMF in the British Virgin Islands.

Up on the ship's bridge, Holt told me this enormously expensive exercise was to better understand the speed and power requirements of this mining technique, which relied on off-the-shelf commercial equipment Magellan had modified for underwater use. His remit was also to quantify the environmental impacts that a future vessel even larger than the 270-foot *Coco* might generate through similar extraction cycles. He told me that before the excursion had started he had been "totally in two minds" about seafloor mining. "But now I've seen how rich the deposit is and how little we've been disturbing the seabed," he said. "We haven't got huge clouds of sediment that are drifting off down in the current, smothering coral reefs, or all this sort of stuff that people are worried about."

Jen Christiansen

I observed the same 12-hour extraction cycle twice during my time onboard. Holt told me that over nearly two months Magellan's teams were focusing on four separate locations in a wider area collectively designated Solwara 1. In each location, the crew would excavate a number of square plots 33 feet on edge and up to 23 feet deep. He said PNG's Mineral Resources Authority, or MRA, had approved the extraction of about 200 tons of material—from an ore body estimated at more than two million tons—for removal and further testing on shore. He also explained that to maximize the clamshell jaws' productivity on the seafloor between each long descent and ascent, Magellan had decided to stockpile more material than the 200 tons permitted for testing—up to 600 tons from each of the four sites—perhaps for collection at a later date. I realized this meant Magellan and DSMF might be digging up more of the seabed than the regulator had anticipated.

As with any mining endeavor, Solwara 1's long-term economic viability would live and die on global metal prices, and in this case the ore's copper concentration was a crucial factor. Two local geologists onboard seemed enthralled by their initial readings. Leaning over the pile of dark-gray rock that had been dumped onto the rear deck—after it had been smashed into pieces by a large drill—Paul Lahari grabbed some samples and carried them into a cramped prefab shipping container that served as a laboratory. "Anything to do with 0.5 or 1 percent, we're already excited," said the Papua New Guinean, who had decades of onshore and offshore mining experience.

He was referring to the typical copper concentrations in ore mined on land. Inside the lab he wielded a small instrument that measures x-ray fluorescence, which he said would reveal the elemental composition of each sample. Soon, on its small digital screen, the instrument began to show matches to elements in the periodic table, as well as their estimated concentration in the sample. For copper, it was 12.33 percent. “That’s 10 times more than we get on land,” Lahari said, his voice rising. He noted that the sampling averages so far on the trip had hovered around 7 percent.

All 200 tons the *Coco* recovered and carried onboard would eventually reach an Australian facility, where the rock would be further pulverized. Much smaller samples would then pass through a gauntlet of geochemical tests—heating, fusing, leaching—and the entire batch would be assigned an industry-recognized average copper concentration, or “grade,” alongside a report on the other metals found, including gold.

Oceanographers have identified massive sulfide deposits across the Atlantic, Pacific, Indian and Arctic Oceans. Small-scale sample drilling has shown that they often contain similarly high concentrations of copper, alongside zinc and lead. Deposits form close to, if not on, the seafloor surface, meaning there’s far less “overburden”—the valueless material that must be removed to access the ore—than in most land-based mines.

Other prospectors have been interested in Solwara’s potential for years. In 2011 executives from Nautilus Minerals, headquartered in Canada, leased the Solwara 1 site from PNG as a 20-year underwater-mining concession. Authorities in the perennially cash-strapped country invested $120 million in the project through a state-owned entity. The country’s taxpayers thus became a junior partner with Nautilus.

At the time, Nautilus was hailed as a pioneer—the only company in the world to hold a license for deep-sea mining. But as the project

progressed, things went sideways. A coastal nation controls resource exploitation in the waters constituting its exclusive economic zone, which reaches 200 nautical miles out from its shoreline in all directions. Any activities in the international waters between nations' economic zones, such as deep-sea mining, are regulated by the International Seabed Authority, or ISA, a body established through a treaty sponsored by the United Nations.

> A Papua New Guinea governor wrote in a statement that he considered the "presence of any [mining] vessel or activity in the area to be illegal."

When PNG issued Nautilus's license in 2011 for operations in its national waters, it had no specific underwater-mining legislation. The MRA, the country's mining regulator, issued the license under rules for land-based mining after Nautilus had carried out impact assessments to earn a separate environmental permit. After false starts in sourcing a ship, in 2014 Nautilus commissioned a Chinese shipyard to build a mining vessel, and Nautilus contracted engineers to develop three enormous, tracked vehicles to break up, churn up and then suck up material from a massive sulfide deposit through a mile-long slurry hose connected to the surface vessel. The technique would mean dumping mining water back into the sea—something other mining operators were planning to do, too.

But Nautilus began burning through up to $2 million a month, according to 2018 financial disclosures, eventually defaulting on payments to the Chinese shipyard before filing for bankruptcy in 2019. Its remaining assets included the mining permit, a few promising core samples, and the three tracked vehicles, only ever tested in shallow waters, that sat rusting on the edge of PNG's capital, Port Moresby. After its insolvency, PNG Prime Minister James Marape told a local newspaper that the country had wasted tens of millions of dollars on a "concept that is a total failure." In 2020 the head of the MRA ruled out any chance of reviving the Solwara project.

I disembarked from the *Coco* less than a day and a half after I had boarded. In blazing afternoon sunshine, a much smaller skiff ferried me back to a remote, pebbly beach on the PNG island of New Ireland. I wanted to know how PNG's officials and citizens felt about the *Coco* pulling up their seafloor. A local driver I had hired drove me in the dark over bumpy coastal roads to a guesthouse in the village of Kono.

The following morning I sat outside at a rickety wood table, sharing a breakfast of fish, yams and crackers with some of the local men. One of them, Jonathan Mesulam, was a spokesperson for the Alliance of Solwara Warriors, a group that has long demanded a ban on deep-sea mining in the Bismarck Sea. A Fiji-based environmental campaigner had introduced me to him via an encrypted messaging app. As I described what I had seen onboard the *Coco*, Mesulam shifted from initially incredulous to increasingly agitated. He walked to the home of Kono's chief, Chris Malagan, to discuss what I had told him ahead of a weekly public meeting Malagan presides over, which attracts many of the village's 700 residents.

Malagan began that afternoon's meeting underneath large shoreline trees. Nearby, children waded out from the beach to cast lines for small fish in the shallows close to more than a dozen mud and straw huts. Adults sitting among the trees listened intently to Mesulam's description of the *Coco*'s operations, which was based on my eyewitness account. Several people stood up to angrily denounce activities they considered threatening to their fish-centered livelihoods.

"People are surprised—they are shocked after learning that the new company's coming back," Mesulam told me as villagers drifted away. "After all our efforts on campaigning against seabed mining, we thought it was a dead issue now," he continued, becoming occasionally tearful. "We don't want to be used as guinea pigs for trial and error," he said. "These metals that are going to be dug out

of our ocean will not benefit anyone from here because nobody here is using electric cars."

The lack of local awareness and the *Coco*'s stockpiling of seafloor material seemed unusual for a 21st-century extraction project. To better understand the political support and permitting process for deep-sea mining, I left New Ireland on a plane headed to Port Moresby. The capital, with its sprawling neighborhoods, is built around a spectacular natural harbor. In a hilltop hotel, I told a lawyer named Peter Bosip that I had recently been onboard a deep-sea-mining vessel. He seemed upset. He told me neither Nautilus's 25-year environmental permit nor the MRA's subsequently issued mining license for Solwara 1 had ever been made public—despite a constitutionally mandated transparency requirement and a decade-long legal battle waged by good-governance and environmental groups. (Parkinson sent me the cover page of the license, but neither he nor Magellan nor PNG regulators provided a full copy.)

Such opaqueness was common in PNG, Bosip told me, but meant it was difficult for local communities to hold international companies to account for potential environmental infractions. Bosip is executive director of the Center for Environmental Law and Community Rights in PNG, a public-interest law firm that sued the government for access to the Solwara permit documents. "In PNG," he told me, "the system is such a way that the responses are not forthcoming." He apparently meant that government ministries, agencies and regulators rarely shared information willingly.

DSMF provided the struggling Nautilus with high-interest loans, and during the 2019 bankruptcy proceedings, the company took possession of Nautilus's Solwara 1 license. A document from the Supreme Court of British Columbia shows that DSMF's listed representatives during those proceedings were Christopher Jordinson, an Australian who'd previously pled guilty to insider trading, and Matthias Bolliger, a Swiss national who was subsequently barred from directorships on the Isle of Man.

Documents from the bankruptcy proceedings show the pair are listed as points of contact for DSMF's largest shareholders: Omani tycoon Mohammed Al Barwani, whose family firm owns oil, gas and mining subsidiaries, and Alisher Usmanov, who is among Russia's wealthiest pro-Putin businesspeople.* Usmanov had been involved in Solwara-based mining for almost 20 years, but now—after Russia's invasion of Ukraine in 2022—he tops worldwide sanctions lists.

In July 2022 DSMF joined forces with SM2, another company founded by Parkinson, who in turn hired his firm Magellan to operate in PNG waters under Nautilus's original license. Parkinson told me that in November 2023 he, Bolliger and Jordinson met with New Ireland's governor. Sometime later various PNG agencies, including the MRA, approved the new mining technique.

I spent days chasing down officials across Port Moresby, trying to get clarity on this approval process. After unanswered e-mails and unreturned phone calls, I finally reached the MRA's managing director, Jerry Garry, by video call. He was in a remote highland region that was slated to host a gold mine, he said, but he told me his officials should be onboard any deep-sea-mining vessel in PNG to monitor operations. When I noted none had been onboard the *Coco,* he insisted he had no idea the *Coco* was even in the Bismarck Sea. Garry never again answered my calls.

PNG's attorney general, Pila Kole Niningi, didn't reply to interview requests. I did reach Fiona Pagla, the PNG Department of Justice's acting director for the national oceans office, who was at a conference in Bali. She told me that she knew nothing about the *Coco* but that if it was conducting marine scientific research, a committee inside her department should have been asked for approval. Hours later, when I pressed her for details in WhatsApp messages, Pagla replied, "No comment."

The country's environment minister, Simon Kilepa, didn't make himself available for an interview. Jude Tukuliya, head of the PNG Conservation and Environment Protection Authority, and officials at the country's National Fisheries Authority did not respond to calls and written questions about the *Coco* and DSMF. Prime Minister Marape's chief of staff insisted the premier would not discuss deep-sea mining.

After returning to London, where I live, I continued my attempted outreach from afar. Late last summer DSMF's website was taken down and replaced with a fresh one featuring a new entity called Sustainable Mining Solutions (SMS), billed as a joint venture between DSMF and Parkinson's SM2. The site repeatedly mentioned Nautilus's mining license and environmental permits—still not public—and said PNG would gain from Solwara 1's profits and mining royalties, with benefits for local people "currently being negotiated." Parkinson had told me soon after I'd left the *Coco* that Magellan and SM2 were not "cutting corners" and were "operating within the laws of that country." He had also said the Australian lab readings indicated Solwara 1 is "a credible source of copper." In response to a request for comment I sent in March by e-mail, DSMF wrote that the results "will be provided to the relevant regulatory authorities in due course, once the analyses by internal and third-party experts are completed."

This past January I finally, and unexpectedly, heard from Julius Chan, a PNG prime minister turned New Ireland governor with a national parliamentary seat. He'd previously said deep-sea miners should engage with islanders to provide confidence that a project wouldn't affect their livelihoods. He wrote in a statement that those involved in Solwara "certainly do not have my government support and approval" and that he considered the "presence of any vessel or activity in the area to be illegal." He died three weeks later at age 85. In its e-mail response, DSMF wrote, "The Solwara 1 project is compliant with the regulations, having secured a valid mining license as defined in the PNG Mining Act, and is a fully permitted

project having met license requirements under relevant Papua New Guinea laws and regulations." It also noted that "the allowable impacts of mining at Solwara 1 are regulated, managed and conducted in accordance with the Mining Law and Environmental Act (2000)."

Mark Smith

The Magellan team onboard the *Coco* had told me it was operating with permission from the MRA, and Parkinson told me before and after my visit to PNG that government officials were aware and supportive of their large-scale extraction tests. Perhaps some people inside the government had not shared details of the *Coco*'s mission as widely as they could have, I reasoned. But when I was onboard, there seemed to be little stopping the Solwara 1 project from scaling up significantly—unless steep capital costs somehow dissuaded deep-pocketed investors or public uproar in PNG forced a rethink among national politicians, who perhaps might have been hoping to recoup the sizable state investment Nautilus once blew through.

What is clear is that deep-sea mining on a commercial scale will begin soon somewhere. Norway, the Cook Islands, Japan and Sweden have approved deep-sea mining in their exclusive economic zones. Norway's offshore-resources agency says the country's waters contain manganese crusts, as well as sulfide deposits, and the government had considered awarding exploitation licenses this year. Authorities in the Cook Islands have issued exploration licenses to three operators surveying for polymetallic nodules. Scientists at the University of Tokyo and collaborating institutions recently confirmed a vast nodule field close to Japan's easternmost island, a tiny atoll called Minamitorishima. Estimates indicate the field contains more than 600,000 tons of cobalt—much more than the total 2023 output from the Democratic Republic of Congo, by far the largest global cobalt producer.

A consortium of government agencies, academic institutions and private enterprises plans to extract Japan's underwater resources in the decades ahead. With enormous deep-sea regions still unmapped, scientists say similar opportunities exist elsewhere. But after a 2023 study found that some polymetallic nodules emitted enough radiation that inappropriate handling could pose health risks, questions have increased about the wisdom of nodule mining. Citing limited scientific data on long-term environmental impacts, many nations, including Germany, Spain and Chile, have called for a pause. Palau and Fiji have advocated for a moratorium, and France wants an outright ban.

The ISA has granted more than 30 exploration licenses for international waters, some for each of the three kinds of deposits. It has repeatedly delayed a framework for exploitation licenses, though, to the frustration of some people in the mining industry. The authority's new secretary-general, Brazilian oceanographer Leticia Carvalho, took charge in January 2025, promising to end what she considers cozy relations between ISA and potential commercial operators. She has also suggested that the new subsea-mining code should be finalized by late this year.

Unlike in the early years of, say, coal mining, environmental scientists are deeply involved in the development of seafloor extraction. But much remains unknown about the impacts. Scant studies exist on the consequences for marine life of sulfide-deposit mining like the *Coco* was carrying out. A case study involving Japanese state entities digging sulfides at a similar depth, several thousand miles north in the Pacific Ocean, gives some idea of what to expect. Researchers assessed the impact on nearby ocean flora and fauna for three years after a brief mining session. They found that populations of organisms less than a tenth of an inch in size may return to normal levels within a year, but larger species may remain depleted more than three years later. That mining lasted only six hours.

In its statement, DSMF wrote, “Extensive scientific studies have enabled SMS to assess the risks to marine ecosystems and carefully weigh them against the damage caused by terrestrial mining.” The new SMS website says mining in Solwara 1 “will not adversely affect the marine life habitat” and that with recolonization efforts, three years after mining ends, the environment around any vents will “resemble the pre-mining condition of biomass and diversity.” Marine scientists I spoke to questioned that assertion. The ecosystem will not recover “unless the chemistry and the substrate and the texture and the morphology of the bottom, and the temperature and everything else, are what they were” before a location was disturbed, says Lisa Levin, professor emerita of biological oceanography and marine ecology at the Scripps Institution of Oceanography in San Diego. “It couldn’t possibly be.” She says certain species exist only near these vents, and after mining it’s “highly likely” those species will become extinct. “People have to be willing to give up the seafloor ecosystems if they want to mine them,” Levin says. She adds that the contamination of fish stocks by chemicals from the seafloor should reasonably concern local societies.

Throughout the world's deep ocean zones, where scientists estimate thousands of species remain undiscovered, heavy mining equipment may harm organisms that are unable to quickly move out of its way. Leaks from mining equipment or mining water dumped from surface vessels could also threaten open-ocean fisheries, and noise and light pollution could impact reproduction or feeding patterns of species already threatened by other human actions. The environmental team onboard the *Coco* was clearly aware of some of these potential consequences.

The juxtapositions I experienced at sea and on land were jarring. The extraordinary scale and power of the *Coco*'s technology, backed by distant billionaires, were in sharp contrast to subsistence communities where villagers paddle canoes into the surf to fish by hand. The informational asymmetry was striking, too: hydrographers, geologists and environmental scientists with millions of data points designed to gauge surroundings—and profits to be realized thousands of miles away—were set against local residents who seemed to lack access to attested Solwara permits, let alone details of possible environmental drawbacks. For the people who live there, short-term benefits—new local jobs, perhaps, or increased government revenues—might never outweigh stress to the ecosystem and a way of life that depends on it.

As this article was going to press, senior PNG officials—including one in the country's Department of Justice—told me the questions I had asked during my reporting had prompted action. In late February the government introduced new mining legislation that, for the first time, includes specific rules for deep-sea mining. The country's Marine Scientific Research Committee, which comprises almost two dozen government entities, passed guidelines that will require future deep-sea-mining licenses to have committee approval. Because the legislation is open to public comment, it is not yet clear whether a new mining law will have retroactive force. If it does, officials told me, DSMF might have to reapply for its

environmental permits and mining license and publish a fresh environmental impact assessment.

Some of the reporting for this story was originally done while Willem Marx was on assignment for PBS.

**Editor's Note (4/28/25): This sentence was edited after posting to describe Alisher Usmanov as a businessperson.*

Willem Marx is a London-based magazine, radio and television journalist, and he is working on a book about a contentious pipeline project in Africa. Marx has written for the *Wall Street Journal*, *Vanity Fair*, *Businessweek*, *Harpers* and *Wired*, among other publications.

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https://www.scientificamerican.com/article/miners-are-pulling-valuable-metals-from-the-seafloor-and-almost-no-one-knows

Mathematicians' Favorite Shapes Hold the Key to Big Mathematical Mysteries

Mathematicians describe the most beautiful and beguiling forms and surfaces they know

By Rachel Crowell & Violet Frances edited by Clara Moskowitz & Jen Christiansen

Violet Frances

When most people think of shapes, they imagine a triangle, a rectangle, or maybe even a fancier- sounding rhombus or trapezoid. But to mathematicians, shapes encompass a vast universe of surprising forms, from one-dimensional loops to polytopes (geometric objects with flat sides that can exist in any desired dimension).

A related category, surfaces—collections of points that form boundaries in 3D space—includes an entire zoo of striking, strange mathematical objects. In this playground of structures and ideas, mathematicians explore, discover new insights and ponder open questions.

Some mathematicians love shapes that are deeply connected to the physical world, such as Borromean rings, which are related to regular hair braids, and the permutahedron, which is the basic shape of a zeolite crystal (a material widely used in industrial applications). Others favor more abstract options that represent higher-dimensional realms seemingly divorced from the world we live in.

We asked mathematicians to choose their favorite shapes and surfaces and tell us why they find them so exciting and intriguing. Here are their edited responses.

The Loop

Violet Frances

My favorite shape is the loop, a circle with all geometric information stripped away, leaving only a free-form one-dimensional object. In fact, there's a sense in which it is the only one-dimensional object. The biggest questions in topology [the branch of math concerned with the properties of shapes that stay constant even when the forms are stretched and warped] concern classifications of closed manifolds, which are the abstract notion of what "shape" means to a topologist. Surprisingly, we have a good sense of what every possible closed manifold looks like, provided it is one-, two- or three-dimensional or five-or-more-dimensional, but we know little about how four-dimensional manifolds can look. In

this framework, the only one-dimensional closed manifold is a loop.

The loop is also ubiquitous throughout different fields of topology, often in a very crucial way. For example, the most fruitful and important invariant in topology is arguably the fundamental group, an algebraic object that counts how many ways a loop can be squeezed inside a space. And knot theory is an entire field of math focusing on the question “What are all the ways a loop can be tangled in three-dimensional space?” There is still so much to be learned about loops. *—Shintaro Fushida-Hardy, Stanford University*

The Complement of a Knot

Violet Frances

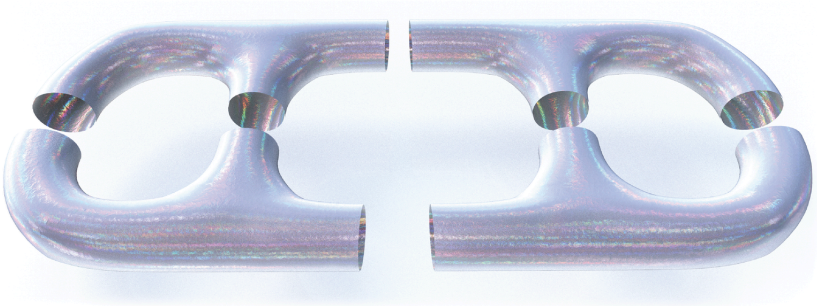
The complement of a knot is everything in three-dimensional space that isn’t the knot. It’s a topological object—if you wiggle the knot around, then its complement also squishes around. In the late 1970s American mathematician Robert F. Riley realized the complement of the figure-eight knot—this flexible topological object—is secretly an impossibly hard geometric diamond.

This is all metaphor—by “geometric diamond,” I mean it isn’t just topological; it has geometry to it, and “diamond” is supposed to make you think of a rigid gemstone. It is a gem, as in a singular, beautiful object, and it is rigid in the sense that you cannot change its geometry—the geometry is unique. “Impossibly hard” is also trying to express this rigidity.

Riley showed that the complement of the figure-eight knot has a complete hyperbolic metric—in fact, a unique such metric. [“Hyperbolic” refers to a hyperbola, an open-ended curve.] This means that, for example, it makes sense to ask what its volume is given this unique metric. (It holds approximately 2.03 units of hyperbolic volume.) Soon after, mathematician William Thurston, then at Princeton University, vastly extended Riley’s insight, showing that in a certain sense almost all knots have hyperbolic complements. Of the 352,152,252 prime knots with up to 19 crossings (classified by Benjamin A. Burton of the University of Queensland in Australia), only 395 are not hyperbolic.

What’s a prime knot? Natural numbers are either composite or prime, depending on whether you can factor them into smaller pieces that then multiply together to give the number you started with. There is a similar situation with knots—instead of multiplication to combine two numbers to make a bigger number, an operation called connect sum combines two knots into a single, bigger knot. A knot is prime if it is not composite—that is, if it cannot be made by summing two smaller knots. People usually care only about prime knots because you can usually understand any composite knot by breaking it up into its prime knot factors first. —*Henry Segerman, Oklahoma State University*

Hyperbolic Pair of Pants

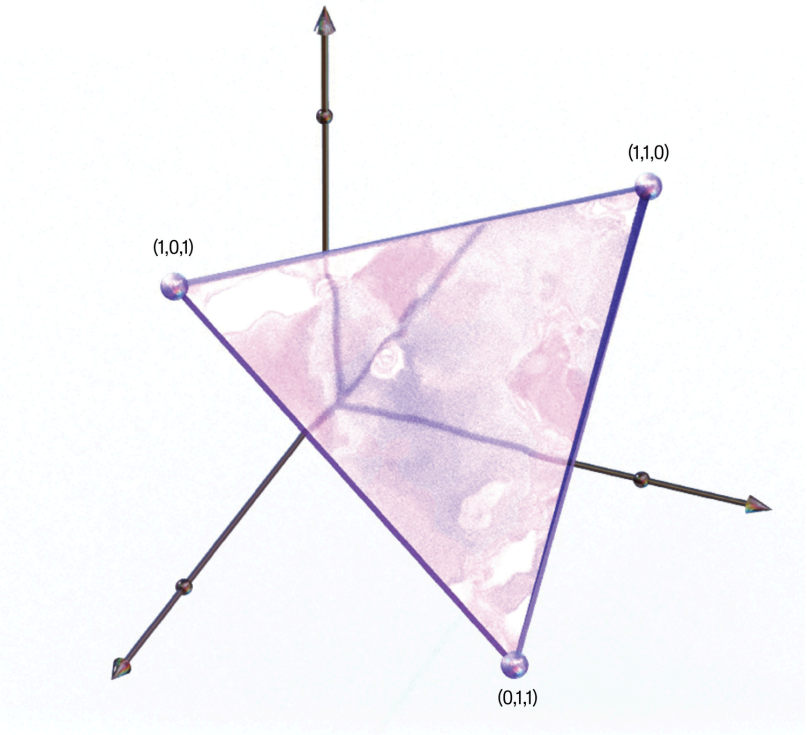


Violet Frances

My favorite shape—and one I think about every day—is called the hyperbolic pair of pants. It is a surface with the shape of a pair of pants, meaning it has three boundary components (a waist and two ankles) and genus 0 (no handle, as opposed to your coffee mug). What makes this shape so special is that to every three lengths *a*, *b* and *c*, we can associate one and only one hyperbolic pair of pants of boundary lengths *a*, *b* and *c*. Thus, the same way that you know how to draw “the rectangle of edges 2 and 3.5,” it makes sense to talk about “the hyperbolic pair of pants of boundaries 1, 6 and 2.4.”

You can play and sew hyperbolic pairs of pants together. When you sew two pairs of jeans along their beltlines, an important decision is whether to line up their buttons and, if not, how much to twist. The amount of twisting is called the twist angle, represented by tau (τ). We can construct every hyperbolic surface by sewing together hyperbolic pairs of pants and describe all of them entirely in terms of the boundary lengths and twist angles in this decomposition. Therefore, hyperbolic pairs of pants are the perfect building blocks of hyperbolic geometry. — *Laura Monk, University of Bristol, England*

Polytopes

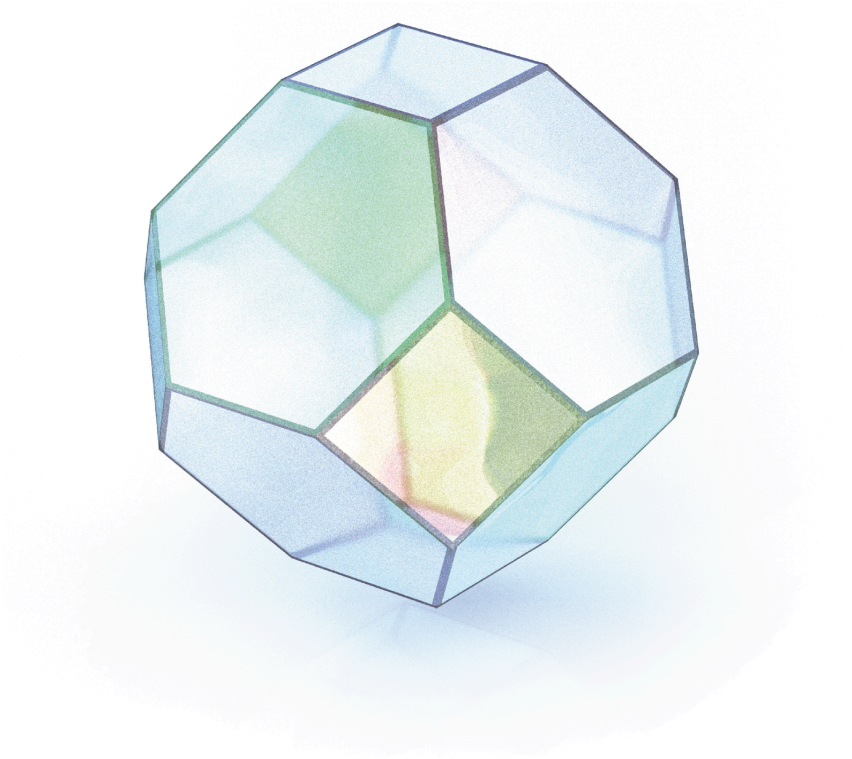


Violet Frances

The shapes I continue to return to in my research career are both commonplace and complex. They are commonplace because we learn about two-dimensional versions of these shapes as children: triangles, squares, dodecahedrons, and other convex polygons [a polygon is any flat shape made with straight lines; a convex polygon has internal angles that are all less than 180 degrees]. They become complex quickly as one considers higher-dimensional versions of them, called polytopes, and recognizes the myriad pure and applied mathematical connections they have. For example, if one has tried to optimize a bounded linear system (for example, to minimize the time required to return electric bikes to their rental stations), then one has encountered a polytope. If one is able to encode data from one mathematical setting as 0/1 coordinates, then the convex hull of those points [the smallest convex shape enclosing the points] describes a polytope. For example, the set of subsets of size 2 over three elements produces the three coordinate points (1,1,0), (1,0,1) and (0,1,1), whose convex hull is a triangle in three-dimensional space. This approach opens up a world of mathematical possibilities and deepens connections between mathematical areas. What may be hard to state in one area may

suddenly be easier to state using polytopal language. It is these kinds of relationships between various mathematical areas, as well as the pursuit of exploring polytopes in their own right, that keep my attention on these simple yet complicated shapes. —*Anastasia Chavez, Saint Mary's College of California*

Permutahedron



Violet Frances

One shape that I find really cool is known as the permutahedron (sometimes spelled permutohedron). This is a very symmetrical convex polytope that exhibits many special properties.

First, what does it mean for a shape to be convex? Think of it like this: if you pick any two points inside the shape and draw a straight line between them, that line will always stay inside the shape.

Second, what is a convex polytope? A convex polytope can be thought of as a shape with flat sides that may exist in any dimension: the zero-dimensional polytopes are points, the one-dimensional polytopes are line segments, and the two-dimensional

polytopes are polygons. In three dimensions, we have polyhedra; in general, we have *d*-polytopes for any dimension *d*. For example, I like to think about convex polytopes in three dimensions as taking some points, throwing them in space and then sealing them in plastic wrap as tightly as you can. As a result, you will get a three-dimensional shape with flat sides. In two dimensions, we can think about points being represented by the heads of nails, wrapping a rubber band around the nails and letting the rubber band snap, creating a polygon.

Now, what is the permutahedron? The *n*-permutahedron is a geometric shape that comes from the mathematical concept of permutations. Say you have a set of numbers 1, 2 and 3. You can arrange those three numbers in different orders: (1,2,3), (1,3,2), (2,3,1), and so on. These different orders are called permutations. The *n*-permutahedron is a shape that captures all the possible ways to arrange the numbers 1 through *n* (for a positive integer *n*). We can define the *n*-permutahedron as the convex hull of all permutations of the vector (1,2,...,*n*).

When $n = 3$, we have six permutations of (1,2,3), which are the vertices of the 3-permutahedron. It is important to note that the 3-permutahedron is a two-dimensional figure “living” in 3-space. The reason behind this is that all the permutations (thought of as points in 3-space) live on the plane where $x + y + z = 6$, thus bringing down the dimension of the polytope.

See, for example, the 4-permutahedron. When $n = 4$, we have $4! = 24$ permutations of (1,2,3,4), which are the vertices of the 4-permutahedron, a 3D polytope that lives in 4-space. This polytope is actually a truncated octahedron, a shape with 14 sides (six squares and eight regular hexagons). And truncated octahedra can create a space-filling tiling of 3-space. —*Andrés R. Vindas Meléndez, Harvey Mudd College*

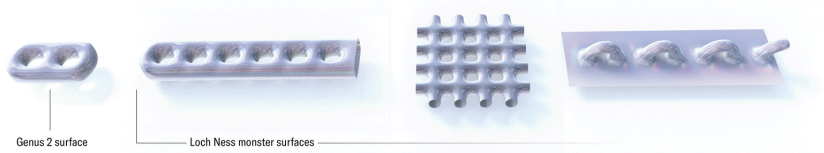
You might have seen this beautifully symmetrical shape in your neighborhood playground; my chemist friend Juliana Velasquez Ochoa of the University of Bologna tells me it is the basic shape in a zeolite crystal. The San Francisco Exploratorium has a pile of identical bright-red permutahedra; when you play with them, you quickly notice that they stack perfectly, tiling [filling] space with no empty space between them.

How do we place 24 vertices in space to make the permutahedron Π_4? My favorite way is to place them in four-dimensional space. The vertices of Π_4 are the $4! = 4 \times 3 \times 2 \times 1 = 24$ orderings (1,2,3,4), (2,1,3,4),..., (4,3,2,1) of the numbers 1,2,3,4. The volume of the permutahedron Π_4 is $32 = 4^{4-2}\sqrt{4}$; we know this because Π_4 is a shadow of the $4(4 – 1)/2 = 6$-dimensional cube, and this fact gives us a way to cut up the permutahedron Π_4 into $16 = 4^{4-2}$ identical boxes of volume $\sqrt{4}$.

The best part of this story is that it is true in any dimension. You can just substitute any value *n* instead of the number 4. (Why don't you try it for $n = 3$?) The vertices of the permutahedron Π_n correspond to the possible orders of *n* objects. So as I alphabetize the stack of final projects of my 18 combinatorics students, I am taking a stroll around Π_{18} in 18-dimensional space.

I love the permutahedron because it is the site of a beautiful, productive dialogue among geometry, algebra and combinatorics [the study of counting, permutations and combinations]. — *Federico Ardila-Mantilla, San Francisco State University*

The Loch Ness Monster Surface

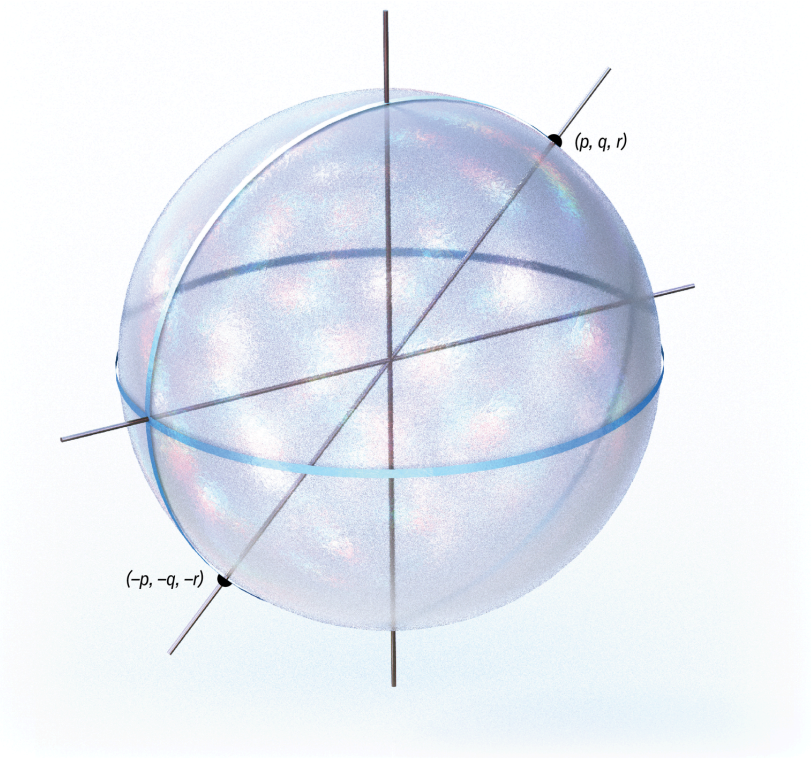


Violet Frances

As someone who studies surfaces for a living, I find it hard to pick a favorite. A common joke in my research area is that everyone's favorite surface is the genus 2 surface [a surface with two holes in it] because it's the lowest-genus (closed) hyperbolic surface and, as such, is often the default example drawn in lectures and talks. Although the genus 2 surface is quite special, I decided to share a little bit about a surface on the other end of the spectrum, an infinite-genus surface called the Loch Ness monster. The Loch Ness monster surface is arguably the "simplest" infinite-type surface, yet its group of topological symmetries known as the mapping class group contains every countable group as a subgroup.

Even stronger, there exists a complete hyperbolic metric on the Loch Ness monster surface whose isometry group (the group of geometric symmetries) is G if and only if G is a countable group. So even though the Loch Ness monster surface may appear quite simple in the wild world of infinite-type surfaces, it captures some pretty neat phenomena. These cool facts were proved by Tarik Aougab of Haverford College, Priyam Patel of the University of Utah and Nicholas G. Vlamis of Queens College in New York City in a 2021 paper entitled "Isometry Groups of Infinite-Genus Hyperbolic Surfaces." *—Marissa Kawehi Loving, University of Wisconsin–Madison*

2D Real Projective Space



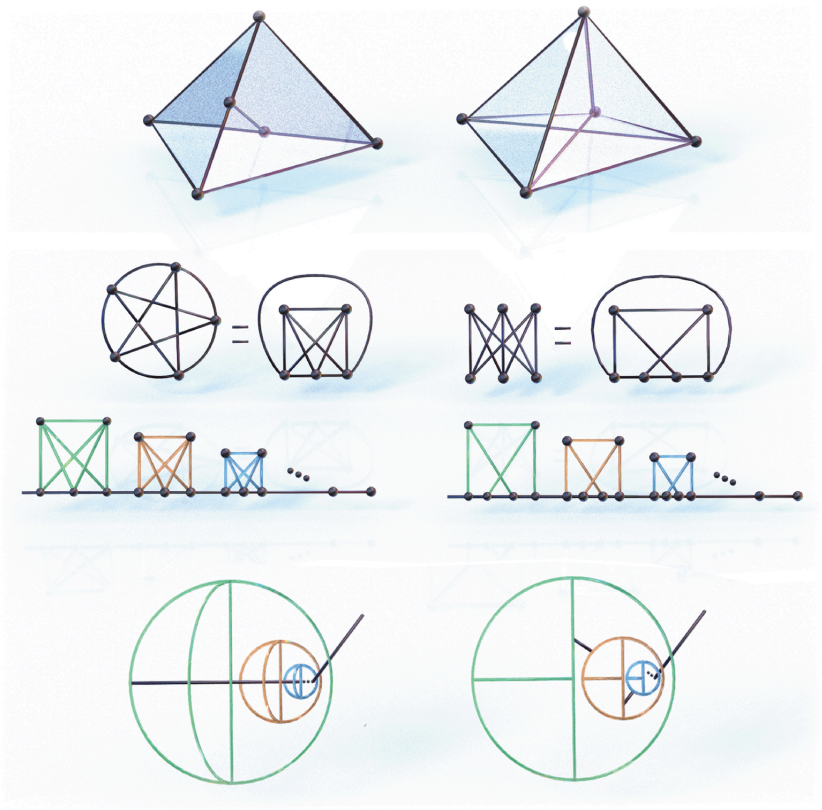
Violet Frances

I’m a topologist, so I’m enthusiastic about a lot of surfaces and shapes, but probably my favorite surface in the sense of a two-dimensional manifold [a surface that behaves like regular space at the local level] is $\mathbb{RP}^2$, or two-dimensional real projective space. In general, $\mathbb{RP}^n$ is the set of lines through the origin in $\mathbb{R}^{n+1}$. So for $\mathbb{RP}^2$, we’re looking at all the lines through the origin in $\mathbb{R}^3$; we can think of it like all the points on the unit sphere, except that any time two points are exactly opposite each other, we treat them as the same because they are on the same line through the origin. This surface can also be thought of in the following way: Take a Mobius band [essentially a strip of paper twisted once with its ends attached] and a disk. Both those things have a boundary, or edge: a circle. If we glue those two boundary circles together, we get two-dimensional real projective space.

This surface is the first step in an important construction in topology, which is to take the set of lines in all spaces $\mathbb{R}^n$, for any dimension n, at the same time. (Equivalently, you can take the set of lines in $\mathbb{R}^\infty$. This space, called $\mathbb{RP}^\infty$, has deep connections to

many features of topology I like, such as realizing fairly abstract algebraic invariants in terms of maps between spaces, studying vector fields on manifolds and studying the behavior of simple symmetries on spaces. —*Kristen Hendricks, Rutgers University*

Curves That Shaped William W. S. Claytor's Mathematics



Violet Frances

These shapes have amazing ramifications in classical topology. A topological image of a curve (shape) is a set of points in the plane that satisfies an equation and has a complicated topological structure.

The shapes shown here come from a 1930 paper by Polish mathematician Kazimierz Kuratowski. In it, he discusses peanian continua, which are, roughly speaking, simple closed curves in the plane or Euclidean 2-sphere. A simple closed curve is a continuous curve that doesn’t intersect with itself and ends at the same point where it started. Some examples of simple closed curves are shapes

represented by circles, ellipses, squares and regular polygons. Kuratowski proved that a peanian continuum containing only a finite number of simple closed curves is homeomorphic [topologically equivalent] to a subset of the plane if and only if it does not contain a topological image of either curve 1 or curve 2. Generally, a homeomorphism results from a continuous deformation of the object (shape) into a new shape, thus possessing similarity of form.

William W. S. Claytor was the third African American to earn a Ph.D. in mathematics. In his 1933 doctoral dissertation, Claytor describes a more general problem that built on Kuratowski's 1930 theorem. That problem is "the characterization of the peanian continua which are homeomorphic with a subset of the surface of a sphere." His dissertation research moved from the case of the Euclidean plane to that of the Euclidean 2-sphere. The Euclidean 2-sphere is similar to a basketball in that it is hollow in the middle. Claytor began his problem by focusing on curves 1 and 2. Whereas Kuratowski had restricted the peanian continua to those containing only a finite number of simple closed curves, Claytor imposed no such restriction. —*Asamoah Nkwanta, Morgan State University*

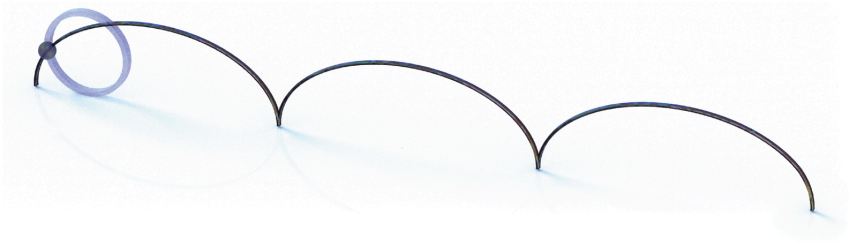
3D Representation of Ribbon Knots

Violet Frances

I find the three-dimensional representation of 4D objects called ribbon knots very cool. Here's how such a representation is constructed: Take a finite collection of disks, cut slits into them, then add bands between the boundaries of the disks that are allowed to pass through these slits. If the boundary of the resulting

picture is a single piece of knotted string, the result is what's called a ribbon disk, and a knot in 3D that bounds such a disk is called a ribbon knot. In the 4D space, which we think of as surrounding the 3D space, there is enough room to undo the insertion and recover a disk (without the slits). Therefore, a ribbon knot is an example of the simplest possible type of knot in 4D, and the process of making a ribbon disk gives us a 3D way to construct it. The slice-ribbon conjecture, a major open problem in low-dimensional topology, says every such simple knot in 4D comes from a ribbon disk. I find the shape fascinating because it is a simple construction that underlies a difficult—and impossible to fully visualize—process in 4D space. Because there is more room than in 3D space, a set of points in 4D that itself constitutes a disk may occupy the space in intricate ways when we view its projection in 3D. —*Christine Ruey Shan Lee, Texas State University*

Cycloid



Violet Frances

The greatest mathematical ideas have three qualities: they are simple to define, they have beautiful and surprising properties, and they generalize in interesting ways. My favorite shape, the cycloid, has all of these.

It arises from a natural question: If you follow a point on the rim of a wheel as it rolls along a road, what shape is traced out? More mathematically, what is the path of a point on the circumference of a circle as it rolls along a straight line? The resulting curve was named the cycloid by Galileo Galilei, and he is just one of the eminent mathematicians who have been fascinated by it (the list

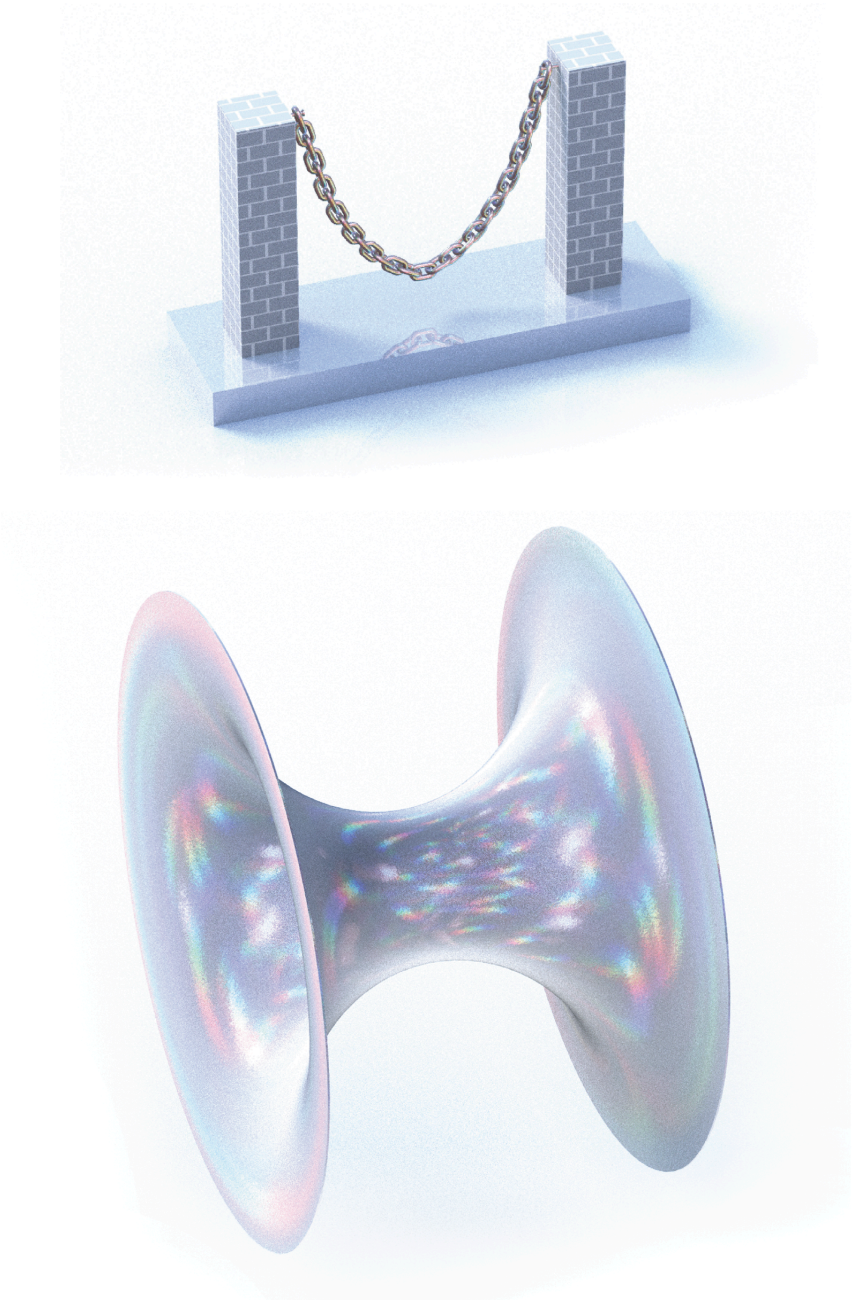
also includes Marin Mersenne, Pierre de Fermat, René Descartes, Blaise Pascal and Isaac Newton). Among the lovely properties of the cycloid is the fact that the area under its arch is exactly three times the area of the generating circle, and its length is exactly four times the diameter of that circle.

But the cycloid appears unexpectedly in a completely different context, the so-called tautochrone problem, which asks: Is there a curve such that a particle on the curve moving under gravity will reach the bottom in the same time no matter where on the curve it is released? The only curve that works is the cycloid. Bizarrely, it's also the solution to another problem about motion.

The brachistochrone problem asks: Given two points *A* and *B*, with *A* higher than *B*, what shape should a wire between them be so that a particle moving along the wire under gravity will travel from *A* to *B* in the shortest possible time? The cycloid is again the answer. And it meets my final criterion for a great mathematical idea: it generalizes in interesting ways. If we can roll a circle along a line, what happens when we roll a circle along a circle? If you roll a circle along the outside of a circle of the same radius, for example, you get the cardioid curve, which crops up all over the place, from the central region of the Mandelbrot set [a set of numbers that produces a famous fractal] to the sound profile of a microphone to that strange pattern of reflected light you see in your coffee cup in the morning.

And what if you roll a line along a circle or another curve? This process results in what's called the involute of the curve. Even here the cycloid has a fascinating property: the cycloid is the only curve that is its own involute. —*Sarah Hart Birkbeck, University of London*

Catenoid



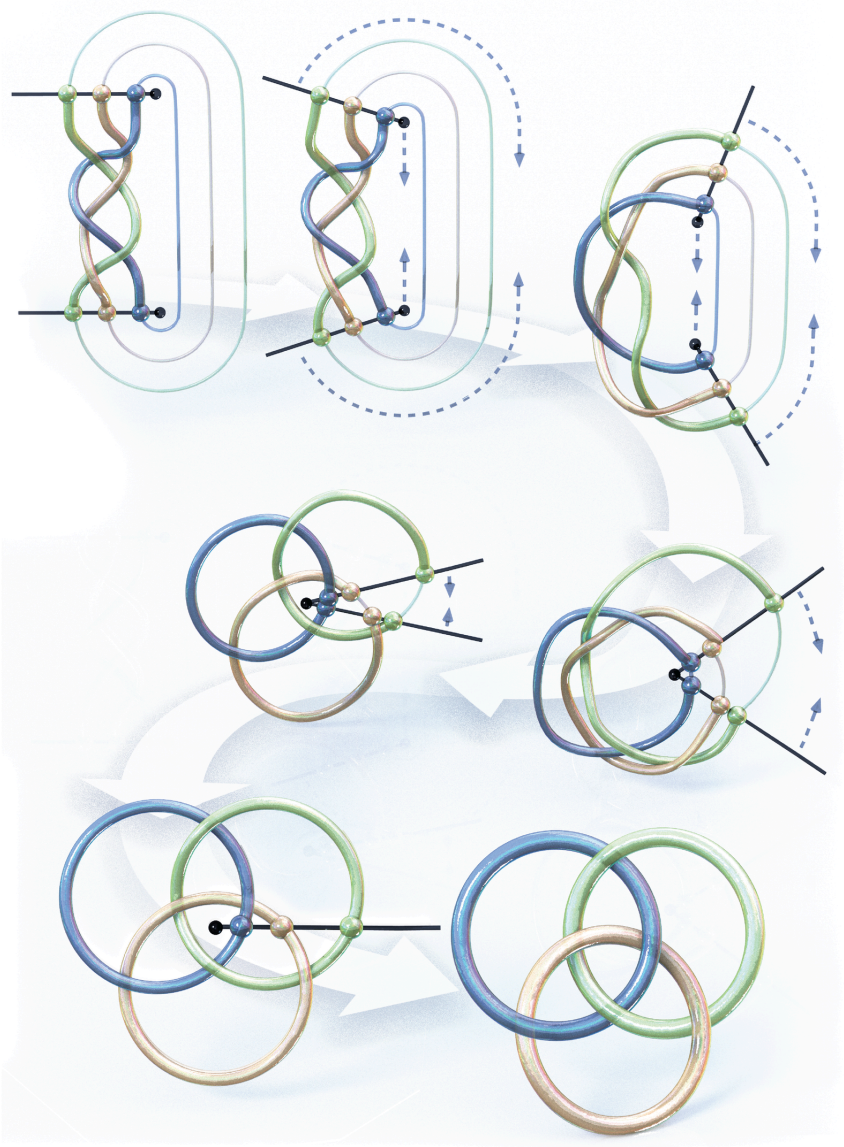
Violet Frances

The catenoid is a fascinating geometric surface obtained when a catenary curve—that is, a curve resembling the shape of a hanging chain—revolves around an axis. This surface has intrigued mathematicians because of its elegant shape and structural properties. It was discovered in 1744 by Swiss mathematician Leonhard Euler, who proved that the catenoid is a minimal surface, meaning it has the least possible area for a given boundary. This property can be beautifully observed with a soap film, which naturally forms a catenoid when stretched between two circular rings. What makes the catenoid even more special is that besides

the plane, it is the only minimal surface that can be obtained as a surface of revolution [a surface created by rotating a curve once around].

Since the 18th century, catenary curves have also been a great source of inspiration in architecture because they distribute forces in a way that makes them ideal for building arches. Catenary arches can be found in many churches and cathedrals, as well as in other architectural masterpieces such as La Pedrera in Barcelona, designed by Antoni Gaudí. Gaudí, a visionary architect, embraced the catenary's natural strength and beauty, incorporating the shape into his designs to create aesthetically stunning and structurally efficient structures. The catenoid and catenary continue to captivate mathematicians and architects with their combination of practicality and elegance. —*Maria Soria Carro, Rutgers University*

Borromean Rings



Violet Frances

My favorite shape is probably the Borromean rings because they embody many seemingly contradictory properties all at once. The three rings are inextricably linked, yet any two are unlinked. They possess a natural symmetry yet cannot be formed from perfect circles. They offer us beauty as well as utility.

The Borromean rings can also be viewed as a “closed” braid. In this context, they provide the simplest nontrivial example of a so-called Brunnian braid, which becomes “unbraided” as soon as one strand is pulled out. It is somewhat challenging (but always possible) to form braids with this property when using four or more strands, but in fact the most familiar of all braids is Brunnian—the

standard hair braid gives rise to the Borromean rings. My own research focuses on symmetries of surfaces, and Brunnian braids play a fundamental role here, arising naturally in algebraic structures that model the motion of points on a plane. —*Tara Brendle, University of Glasgow*

Rachel Crowell is a Midwest-based writer covering science and mathematics. Follow Crowell on Twitter @writesRCrowell

Violet Frances began her illustration career at *Scientific American* in the mid-1990s. Her award-winning work has been featured in publications such as *National Geographic*, *Wired* and the *Atlantic*. Her work can be seen at violetfrances.com

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https://www.scientificamerican.com/article/these-mysterious-shapes-are-at-the-heart-of-maths-biggest-puzzles

A Deadly Parasite Threatens Bees and 130 Crops They Help Grow

Scientists are racing to stop a tiny mite that could devastate the pollinators and agriculture

By Hannah Nordhaus edited by Josh Fischman

A young honeybee, vulnerable to parasitic mites, comes out of its cell in a hive.
Ingo Arndt

Sammy Ramsey was having a hard time getting information. It was 2019, and he was in Thailand, researching parasites that kill bees. But Ramsey was struggling to get one particular Thai beekeeper to talk to him. In nearby bee yards, Ramsey had seen hives overrun with pale, ticklike creatures, each one smaller than a sharpened pencil point, scuttling at ludicrous speed. For each parasite on the hive surface, there were exponentially more hidden from view inside, feasting on developing bees. But this quiet beekeeper’s colonies were healthy. Ramsey, an entomologist, wanted to know why.

The tiny parasites were a honeybee pest from Asia called tropilaelaps mites—tropi mites for short. In 2024 their presence

was confirmed in Europe for the first time, and scientists are certain the mites will soon appear in the Americas. They can cause an epic collapse of honeybee populations that could devastate farms across the continent. Honeybees are essential agricultural workers. Trucked by their keepers from field to field, they help farmers grow more than 130 crops—from nuts to fruits to vegetables to alfalfa hay for cattle—worth more than $15 billion annually. If tropi mites kill those bees, the damage to the farm economy would be staggering.

Other countries have already felt the effects of the mite. The parasites blazed a murderous path through Southeast Asia and India in the 1960s and 1970s. Because crops are smaller and more diverse there than in giant American farms, the economic effects of the mite were felt mainly by beekeepers, who experienced massive colony losses soon after tropilaelaps arrived. The parasite spread through northern Asia, the Middle East, Oceania and Central Asia. And now Europe. That sighting sounded alarms on this side of the Atlantic because the ocean won't serve as a barrier for long. Mites can stow away on ships, on smuggled or imported bees. "The acceleration of the tropi mite's spread has become so clear that no one can deny it's gunning for us," said Ramsey, now an assistant professor at the University of Colorado Boulder, on the Beekeeping Today podcast in 2023.

Ramsey, who is small and energetic like the creatures he studies, had traveled to Thailand in 2019 to gather information on techniques that the country's beekeepers, who had lived with the mite for decades, were using to keep their bees alive. But the silent keeper he was interviewing was reluctant to share. Maybe the man feared this nosy foreigner would give away his beekeeping secrets —Ramsey didn't know.

But then the keeper's son tapped his father on the shoulder. "I think that's Black Thai," he said, pointing at Ramsey. On his phone, the young man pulled up a video that showed Ramsey's YouTube alter

ego, “Black Thai,” singing a Thai pop song with a gospel lilt. Ramsey, who is Black—and “a scientist, a Christian, queer, a singer,” he says—had taught himself the language by binging Thai movies and music videos. Now that unusual hobby was coming in handy.

> Without bees the almond yield drops drastically. Other foods, such as apples, cherries, blueberries, and some pit fruits and vine fruits, are similarly dependent on bee pollination.

The reticent keeper started to speak. “His face lit up,” Ramsey recalls. “He got really talkative.” The keeper described, in detail, the technique he was using to keep mite populations down. It involved an industrial version of a caustic acid naturally produced by ants. Ramsey thinks the substance might be a worldwide key to fighting the mite, a menace that is both tiny and colossal at the same time.

Ramsey first saw a tropilaelaps mite in 2017, also in Thailand. He had traveled there to study another damaging parasite of honeybees, the aptly named *Varroa destructor* mites. But when he opened his first hive, he instead saw the stunning effect of tropilaelaps. Stunted bees were crawling across the hive frames, and the next-generation brood of cocooned pupae were staring out of their hexagonal cells in the hive with purple-pigmented eyes, exposed to the elements after their infested cell caps had been chewed away by nurse bees in a frenzy to defend the colony. At the hive entrances, bees were trembling on the ground or wandering in drunken circles. Their wings and legs were deformed, abdomens misshapen, and their bodies had a greasy sheen where hairs had worn off. The colony was doomed. “I was told there was no saving that one,” Ramsey says. He had never seen anything like it.

When he got home, he started reading up on the mites. There was not much to read. Somewhere in Southeast Asia in the middle of the last century, two of four known species of tropilaelaps

(*Tropilaelaps mercedesae* and *T. clareae*) had jumped to European honeybees from *Apis dorsata*, the giant honeybee with which it evolved in Asia. Parasites will not, in their natural settings, kill their hosts, “for the same reason you don’t want to burn your house down,” Ramsey said at a beekeeping conference in 2023. “You live there.”

A tiny tropi mite (*on bee at left*) crawls on a bee.
Syzygy Media

The giant honeybees in Asia, a species not used in commercial beekeeping, long ago had reached a mutual accommodation with the mites. But the European bees that Asian beekeepers raised to make honey were entirely naïve to the parasites. When the mites encountered one of those colonies, they almost always killed it. Because beekeepers cluster their beehives in apiaries, moving them en masse from one bee yard to the next, the mite could survive the loss of its host colony by jumping to a new one. “It would normally destroy itself,” Ramsey said at the conference, “if not for us.”

Kept alive by human beekeepers, the mite moved through Asia, across the Middle East and, most recently, to the Ukraine-Russia border and to the country of Georgia. “It is westward expanding, it is eastward expanding, it is northward expanding,” says University of Alberta honeybee biologist Olav Rueppell. This move into Europe is ominous, Ramsey and Rueppell say. Canada has, in the

past, imported queen bees from Ukraine. If the mite arrived in Canada on a Ukrainian bee, it could be a matter of only weeks or months before it crossed the northern U.S. border.

> Today between a quarter and half of U.S. bees die every year, forcing keepers to continually buy replacement “packages” of bees and queens to rebuild.

The almond industry would be especially hard-hit by the mite. Two thirds of the national herd of commercial bees—about two million colonies—are trucked to California’s Central Valley every February to pollinate nearly 1.5 million acres of almond trees. Without bees the almond yield drops drastically. Other foods, such as apples, cherries, blueberries, and some pit fruits and vine fruits, are similarly dependent on bee pollination. We wouldn’t starve without them: corn, wheat and rice, for instance, are pollinated by wind. But fruits and nuts, as well as vegetables such as broccoli, carrots, celery, cucumbers and herbs, would become more scarce and more expensive. Because the cattle industry depends on alfalfa and clover for feed, beef and dairy products would also cost a lot more.

Damage from tropilaelaps, many experts say, could vastly exceed the harm seen from its predecessor pest, the *V. destructor* mite. The varroa scourge arrived in the U.S. in 1987, when a Wisconsin beekeeper noticed a reddish-brown, ticklike creature riding on the back of one of his bees. Like tropilaelaps, varroa mites originated in Asia and then swept across the world. At first beekeepers were able to keep managed colonies alive with the help of easy-to-apply synthetic pesticides. But by 2005 the mites developed resistance to those chemicals, and beekeepers suffered the first wave of what has become a tsunami of losses. Today between a quarter and half of U.S. bees die every year, forcing keepers to continually buy replacement “packages” of bees and queens to rebuild. This past winter keepers saw average losses ranging upward of 70 percent. Scientists believe varroa mites are culprits in most of those losses, making bees susceptible to a variety of environmental insults, from

mite-vectored viruses to fungal infections to pesticides. “In the old days we were shouting and swearing if we had an 8 percent dud rate; now people would be happy with that,” says beekeeper John Miller. He serves on the board of Project *Apis m.* (PAm), a bee-research organization that is a joint venture of the beekeeping and almond industries and was one of Ramsey’s early funders.

When Ramsey joined the University of Maryland’s bee laboratory as a grad student in 2014, he began working on varroa. He discovered that the mites fed not on the bloodlike hemolymph of adult bees, as generations of scientists before him had assumed, but on “fat bodies,” organs similar to the liver. “For the past 70 years research done around varroa mites was based on the wrong information,” Ramsey says. (Recently published research indicates that the mites also feed on hemolymph while reproducing in a developing brood.)

Ramsey’s finding helped to explain how varroa mites make the effects of all the other insults to honeybee health—pesticides, pathogens, poor nutrition—so much worse. Honeybees’ detoxification and immune systems reside in the fat bodies, which also store the nutrients responsible for growth and for protein and fat synthesis. Bees’ livers protect them from pesticides, Ramsey says. But when varroa mites attack honeybee livers, the pollinators succumb to pesticide exposures that would not ordinarily kill them.

Entomologist Sammy Ramsey says such mites can destroy the American bee population.
Syzygy Media

Now Ramsey is going after tropilaelaps as well as varroa mites. He continues his research into countermeasures and teaches both entomology and science communication classes in Boulder. In the years since he first sang as Black Thai, he has also become “Dr. Sammy,” a popular science communicator who is using his growing social media platform to sound the alarm about the parasites.

In April 2024 I was watching him lead a graduate seminar when his watch chimed. “There’s a freezer alert in my lab,” he said. The temperature appeared to be off. We climbed the stairs to his lab overlooking the university’s soccer fields and examined the freezer, which didn’t seem to be in any immediate danger. Inside, stacked in boxes, lay an extensive archive of honeybees and mites that prey on them. Ramsey pulled out a tube of tropi mites.

It was easy to see the enormity—or rather the minusculity—of the problem. The mites are about half a millimeter wide, one-third the size of varroa—“on the margins of what we are capable of seeing with the unassisted eye,” Ramsey says. Seen on video, they crawl so quickly that it looks as if the film speed has been doubled or tripled. Unlike varroa mites, which are brownish-red and relatively easy to spot, to the naked eye tropi mites are “almost devoid of

color," says Natasha Garcia-Andersen, a biologist for the city of Washington, D.C., who traveled to Thailand in January 2024 with a group of North American apiary inspectors to learn about the mites. "You see it, and you can't tell—Is that a mite or dirt or debris?"

Auburn University entomologist Geoff Williams led that Thailand mission. "There's a decent chance that inspectors might be the first ones to identify a tropi mite in North America," Williams says. The Thailand journey allowed them to see firsthand what they might soon be contending with. "It was eye-opening, watching these bee inspectors saying, 'Holy crap, look at these tiny mites. How are you supposed to see that?'"

Daniel P. Huffman; Source: Mallory Jordan and Stephanie Rogers, Auburn University. November 5, 2024, map hosted by Apiary Inspectors of America (*reference*); Data curated by: Rogan Tokach, Dan Aurell, Geoff Williams/Auburn University; Samantha Brunner/North Dakota Department of Agriculture; Natasha Garcia-Andersen/District of Columbia Department of Energy and the Environment

Rather than looking for the mites, Thai beekeepers diagnose tropilaelaps infestations by examining the state of their bees, says Samantha Muirhead, provincial apiculturist for the government of Alberta, Canada, and another of the inspectors on the Thailand expedition. "You see the damage," she says—uncapped brood cells, chewed-up pupae, ailing adults. An unaccustomed North American

beekeeper, however, would probably attribute the destruction to varroa mites. “You have to change the way you’re looking,” she says.

Williams and his team at Auburn are also investigating alternative ways of detection. They are working to develop environmental DNA tests to identify the presence of tropilaelaps DNA in hives. Inspectors would swab the frames or bottom boards of “sentinel hives”—surveillance colonies—to detect an invasion. But any systematic monitoring for tropi mites using this kind of DNA is still years away.

For now scientists are struggling to formulate a plan of action against a menace they don’t fully understand. “We have this huge void of knowledge,” says California beekeeper and researcher Randy Oliver. Scientists don’t know how the mites spread between colonies. Where do they go when colonies swarm? No one has any idea. Can they infect other vulnerable bee species? Do they feed on fat bodies, hemolymph, some combination of the two, or something else entirely? Studies show that tropi mites carry at least two of the same viruses as varroa mites. How many more might they carry? “Part of the rush to action now is the paucity of information,” Rueppell says.

Existing varroa research does provide some knowledge by analogy, but there are several differences between the two mites. Varroa mite populations double in a month, for instance, but tropilaelaps populations do so in a matter of days. Varroa mites tend to bite their bee victims only once; tropi mites feed from multiple entry wounds, creating disabling scar tissue. And for many years scientists thought tropi mites couldn’t survive in colder climates like that of the northern U.S., because the parasites appeared to have a significant evolutionary disadvantage compared with varroa: Tropi mites can feed only on developing bees because their small mouths can’t penetrate adult bee exoskeletons. Queens stop laying eggs in cold weather, so in theory tropi mites shouldn’t have

enough food to last the winter. But about a decade ago the mites were found in colder regions of Korea—and then in northern China and Georgia. “We thought they wouldn’t survive in colonies that overwinter,” says Jeff Pettis, a former U.S. Department of Agriculture research scientist who now heads Apimondia, an international beekeeping federation. “We know they get through the winter now,” he says. Scientists just don’t know how.

> “It’s worse than varroa, and I don’t think we’ll ever be prepared fully.” —John Miller, *beekeeper*

One theory is that the mites disperse onto mice or rats that move into beehives during the cold months—the 1961 paper that first described tropilaelaps noted there were mites on rats in the Philippines. Scientists are exploring other overwintering theories as well. Perhaps the mites feed for brief, broodless periods on other pests in the hive, such as hive beetles and wax moths.

Another possibility, highlighted by Williams’s recent research, is that more bee larvae may persist in colder climates than previously thought, perhaps enough to feed the mites. His team has found small amounts of brood snug in wax-covered cells in hives as far north as New York State and Oregon in the winter. “My gut feeling is that these colonies might have a little bit of brood through the winter,” Williams says.

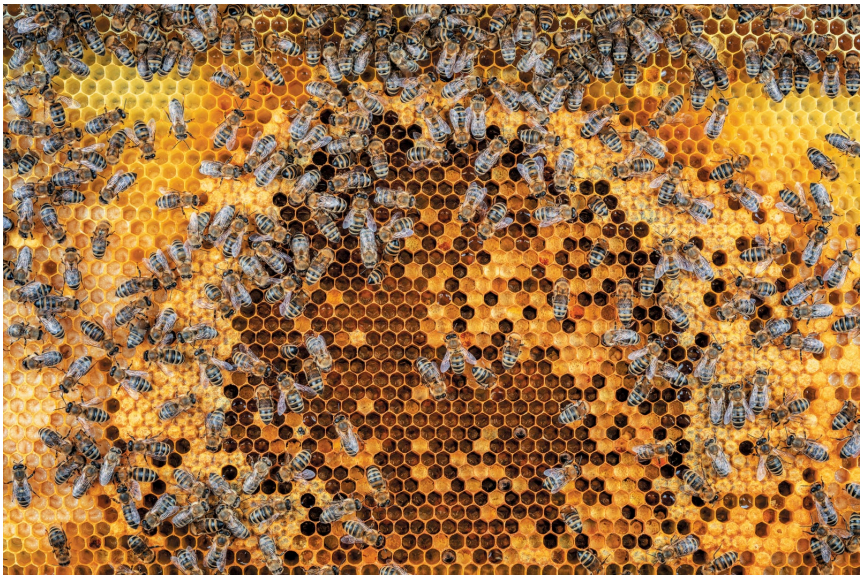
In 2022 Ramsey returned to Thailand and set up several research apiaries for what he calls his “Fight the Mite” initiative, testing different treatments to kill tropi mites. It isn’t easy. Whereas varroa mites live on adult bees for much of their life cycle, tropi mites live mostly inside brood cells, safe from most pesticides, which can’t penetrate the wax-capped hexagons.

A close-up view of a tropi mite.
Syzygy Media

But Ramsey learned from the Thai beekeepers he met on his 2019 visit that many of them had been using formic acid, the compound produced by ants that can get into capped cells. The beekeepers had been dipping paint stirrers in industrial-grade cans of the stuff and sticking the blades under hive entrances. Fumes then seeped through the wax caps and killed the mites. Ramsey experimented with various formulations and applications in 2022 and found that this method worked, although the chemical is highly volatile, caustic and difficult to apply. It's hard on both bees and beekeepers. "Heat treatments"—heating hives to more than 100 degrees Fahrenheit for two-plus hours—also took a dent out of mite populations in Ramsey's tests.

Williams, meanwhile, has been studying "cultural techniques" for controlling the mites, such as strategic breaks in brood cycles. Beekeepers in Thailand typically keep fewer bees in relatively small colonies, much tinier than the thousands or tens of thousands that some North American commercial outfits maintain. And when mite loads get bad, some Thai beekeepers also will discard their brood completely and start over. "They're not afraid to quite literally throw away brood frames when they have mites," Williams says.

These strategies are difficult to apply at the scale of North American industrial apiculture. But large commercial outfits, which can keep anywhere from dozens to tens of thousands of colonies, may be able to adopt other tactics such as “indoor shedding”—storing all their hives in refrigerated sheds for a number of weeks to force an extended brood break. It’s likely that an effective approach will employ not one silver bullet but rather some combination of strategies—chemicals, heat, brood breaks—to avoid developing resistance. “You want to be able to rotate treatments to pound away at the mite,” Oliver says.



Honeybees crawl over a comb of hexagonal hive cells, some filled with honey and pollen.
Ingo Arndt

These different techniques highlight the need for both varied approaches and, Ramsey believes, a varied group of scientists attacking the problem. “To study insects is to study diversity,” Ramsey says. “It is not a glitch in biology that the most successful group of animals on this planet is the most diverse group of animals. One of the key features of diversity is the capacity to solve problems in different ways.” To stave off the tropi mite, scientists will need to attack the problem from every angle they can conceive.

On an afternoon in late May 2024, Ramsey, clad in a protective suit, opened a test hive in a holding yard on the east side of

Boulder. The last cold day of spring was behind us, and everything had come into bloom at once—a riot of flowering locust, linden, lilac; glowing hay fields; distant, rock-spiked mountains curving northward out of sight. Massive bumblebees flew from flower to flower on a black locust tree above us, hovering like dark blimps in the sky.

These were supposed to be Ramsey's "pampered" bees, a control group to compare with more infested hives. They had, of course, been spared the ravages of tropi mites, which were still an ocean away. But they had been given frequent treatments for varroa mites. On the first frame Ramsey pulled, however, he saw sick bees everywhere. "This young lady clearly has a virus," he said, noting a female's "greasy," prematurely bald abdomen. He pointed to a sinister dot the color of dried blood between another bee's wings: a varroa mite. The bees were cranky, swooping and dive-bombing, and there weren't enough brood cells on the frame. Ramsey sang to the bees in his gospel-tinged tenor, puffing at the hive with his smoker. "It seems like some of our best treatments for varroa mite are failing," he said, examining another frame.

The American practice of beekeeping is built on abundance—stacks of bee boxes, fields of flowers, vats of honey, teeming hives and expanses of wax-capped brood. But in Thailand, where tropilaelaps has been established for decades, beekeeping often is an exercise in scarcity—small colonies, meager honey production, uncapped pupae. Beekeepers there think far less about varroa mites than they worry about tropilaelaps, which outcompeted varroa years ago.

There are so many threats facing modern honeybees—a daunting diversity, and we are ready for none of them. In 2023 the Georgia Department of Agriculture confirmed the presence of the yellow-legged hornet—*Vespa velutina*—in the U.S. Like the northern giant "murder" hornet found in Washington State in 2019 and declared eradicated in the U.S. last year, the yellow-legged insect is a

“terrible beast,” says PAm executive director Danielle Downey. It hovers in front of beehives—a behavior called hawking—and rips the heads, abdomens and wings from returning foragers like a hunter field-dressing game. Then the hornet takes the thorax back to its nest. When the hornet first arrived in Europe, beekeepers lost 50 to 80 percent of their colonies. “The thing eats everything. One nest can eat 25 pounds of insects,” Downey says. “We’ve identified a lot of problems. How many crises can we handle?”

In the spring of 2024, when the research paper confirming tropi mites were in Europe was published, Canada suspended all imports of Ukrainian hives and queens. For now that means this route for the mite’s arrival in North America is off the table. But trade—legal or surreptitious—could start again, and with the mites’ ferocious reproduction rates, it takes only one female to infect an entire continent. So this reprieve is probably only temporary. “We know the pathway and the threat it poses,” Downey says.

A beekeeper with an infestation could spread the mite across the continent within a year; beehive die-offs would probably begin several months later. “It’s worse than varroa, and I don’t think we’ll ever be prepared fully,” Miller says.

But Ramsey and his colleagues are racing to make sure they know every option available to them—formic acid, heat treatments, rotation, brood breaks—so that when the tropilaelaps mite does, at last, inevitably arrive, they will be ready. Researchers and beekeepers, Ramsey says, are trying to murder these parasites.

Hannah Nordhaus writes about biodiversity, history and the natural world for publications such as *National Geographic*, *Wired*, *Outside*, and the *Wall Street Journal*. She is author of the books *The Beekeeper's Lament* (2011) and *American Ghost* (2015), both published by HarperCollins. Nordhaus is a National Geographic Storytelling Fellow and Explorer and journalist in residence at the University of Colorado Boulder.

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https://www.scientificamerican.com/article/a-new-bee-crisis-could-make-your-food-scarce-and-expensive

The Nontoxic Cleaner That Kills Germs Better Than Bleach—And You Can Use It on Your Skin

Hypochlorous acid is safe enough to spray in your eyes yet more effective than bleach. Why isn't it everywhere?

By Jen Schwartz edited by Seth Fletcher

Richard Borge

As norovirus surged across the U.S. last winter, the only thing more horrifying than descriptions of the highly contagious illness—violent projectile vomiting!—was learning that nothing seemed to kill the microbe that causes it. Hand sanitizers made with alcohol are useless. Water needs to be above 150 degrees Fahrenheit to kill the virus, which is too hot for handwashing. Rubbing with soapy water and rinsing can physically remove the virus from your hands and send it down the drain but won't effectively kill it. Bleach dismantles norovirus, but you can't spray bleach on skin or food or many other things, and norovirus can live on surfaces for weeks.

During the early days of the COVID pandemic, however, I had learned about a disinfecting agent called hypochlorous acid, or HOCl. My dad, a now retired otolaryngologist, had been

wondering whether there was something he might put up patients' noses—and his own—to reduce viral load and decrease the chance of COVID infection without, of course, irritating the mucosa or otherwise doing harm. He was imagining a preventive tool, another layer of protection for health-care workers in addition to masks and face shields.

Hypochlorous acid is a weak acid with a pH slightly below neutral. It should not be confused with sodium hypochlorite (NaClO), the main active ingredient in household bleach products, even though they both involve chlorine. Chemically, they are not the same. Sodium hypochlorite is a strong base with a pH of 11 to 13, and when added to water for consumer products it can be irritating and toxic. Hypochlorous acid, in contrast, is safe on skin.

All mammals naturally make hypochlorous acid to fight infection. When you cut yourself, for instance, white blood cells known as neutrophils go to the site of injury, capturing any invading pathogens. Once the pathogen is engulfed, the cell releases biocides, including hypochlorous acid, a powerful oxidant that kills invading microbes within milliseconds by tearing apart their cell membranes and breaking strands of their DNA.

> Hypochlorous acid is a well-studied disinfectant that appears to be extremely effective and safe—so why isn't it a household name?

The synthetic form of hypochlorous acid destroys a broad spectrum of harmful microbes—including highly resistant spores and viruses such as norovirus. Like most disinfectants, it kills pathogens by penetrating their cell walls. But compared with bleach, hypochlorous acid has been shown to be more than 100 times more effective at much lower concentrations, and it works much faster.

Hypochlorous acid isn't new. It's listed as one of the World Health Organization's essential medicines and is approved by the U.S.

Food and Drug Administration for use on food products and in certain clinical applications. It's increasingly used in industrial and commercial settings, such as water-treatment plants, hospitals and nursing homes. It doesn't irritate the skin, eyes or lungs. In fact, optometrists use it to clean eyes before procedures, and people have been treating wounds with it for more than a century. It breaks down quickly, doesn't produce toxic waste, and isn't harmful to animals or the environment. The U.S. Environmental Protection Agency lists it as a surface disinfectant for the COVID-causing virus SARS-CoV-2.

Hypochlorous acid is a well-studied disinfectant that appears to be extremely effective and safe—so why isn't it a household name?

Scientists have known about the powers of hypochlorous acid for nearly 200 years. In 1834 French chemist Antoine-Jérôme Balard made hypochlorous acid when he added a dilute mix of mercury oxide in water to chlorine gas. Later in the 19th century, English chemist and physicist Michael Faraday developed a technique for synthesizing HOCl from salt and water via a process called electrochemical activation.

Before the advent of antibiotics, hypochlorous acid was a go-to disinfectant. It was used as a wound sanitizer during World War I. The authors of a 1915 article in the *British Medical Journal* set out to investigate antiseptics that could be used to dress wounds in the field. They compared the efficacy of sodium hypochlorite (bleach) with that of hypochlorous acid and "found that hypochlorous acid is a more potent germicide than its salts." They "accordingly devised a method in which the free acid is employed as the antiseptic agent."

For all its benefits, hypochlorous acid solution has one major weakness: it's highly unstable. It remains stable only in a solution with a pH between about 4 and 6. The solution is still made using salt, water and electricity through the process of electrolysis.

Within minutes of exposure to light or air hypochlorous acid starts to deteriorate back into salt water, making it useless as a disinfectant. If the solution were to get too acidic, it would start converting into chlorine gas. If it were to get too alkaline, it would gain a higher percentage of hypochlorite. This lack of shelf stability is the biggest reason hypochlorous acid sprays never became a staple of the cleaning-products aisle.

Richard Borge

For decades hypochlorous acid lingered in the background, used as a disinfectant in specific industrial and commercial contexts that could justify a pricey, on-site manufacturing process to create products on demand. But COVID accelerated the need for different methods of disinfection that would be safe, effective and easy to use in a wide range of environments. According to an article in the

magazine *Health Facilities Management*, during the pandemic "many countries introduced continuous HOCl misting and fogging tunnels for entry and exit corridors at mass transit facilities." Since then, use of HOCl in places such as kitchens, gyms, nursing homes and medical offices has been rising significantly.

Hypochlorous acid consumer products are now proliferating, thanks to the development of new manufacturing processes that reportedly make an extended shelf life possible while keeping costs low. The more reputable of these companies claim their products are effective within two years of the manufacturing date stamped on the bottle if stored correctly (ideally at room temperature, away from sunlight).

Most common are surface sanitizers sold by the bottle and marketed as all-purpose disinfectants for your home, although pure hypochlorous acid isn't really a cleaner—it's not meant to get rid of grime and grease. Like all disinfectants, once hypochlorous acid is applied, it must be left to sit for a period of time. But unlike some germicides that require up to 10 minutes to kill harmful stuff, hypochlorous acid requires only one minute. You don't have to wipe it up, either, but because it doesn't dry quickly, I found it was easier to do so on hard surfaces such as counters.

A frustrating thing about the finicky nature of hypochlorous acid is that you can't really decant it from its original bottle into a smaller one without potentially affecting its quality and longevity. When I needed hypochlorous acid that was suitable for air travel, I had to buy a two-ounce bottle of Magic Molecule, an FDA-cleared product launched in 2023. These bottles are conveniently sized but don't last long, and not being able to refill them results in significant plastic waste.

A customer was sprayed with fogged hypochlorous acid solution at a pub entrance in Tokyo in May 2020 during the COVID pandemic. Fogging certain surfaces may be useful; fogging people probably isn't.
Kyodo News via Getty Images

Other companies have taken a different approach to the shelf-life problem. Force of Nature, for example, sells countertop electrolysis machines for home use. The idea is that you can make as much disinfectant as you need for a week or two, as often as you want, using salt tablets you buy from the company. The process takes about eight minutes. Force of Nature also includes vinegar in its formulation, which gives the product cleansing abilities that the company recommends for use on hard surfaces or carpets. Other

businesses sell devices that let you add your own salt. In online forums dedicated to fans of hypochlorous acid, members discuss how they use these devices. Some use pH test strips to make sure each batch of hypochlorous acid is within the correct range. Some people, however, are skeptical that at-home machines can consistently make pure HOCl.

Last December, troubled by Reddit posters' descriptions of suffering with norovirus, I bought a range of products from Briotech, a company based in Washington State that has been around for years and has coordinated its research with the University of Washington. It sells "pure" hypochlorous acid, as well as some skin-care products. It claims its proprietary manufacturing processes extend the shelf life of its HOCl to up to two years, although the company recommends that you use its products within six months of opening the bottle.

Briotech sells different concentrations and formulations, including a "skin renew serum" at 0.018 percent concentration (or 180 parts per million) and a stronger gel for taking care of body piercings. Magic Molecule calls its hypochlorous acid an "antimicrobial skin cleanser" under the umbrella of "wound care," marketing it as a treatment for acne, eczema, rashes, bug bites, and other concerns. It's currently sold online and, as of this year, at the beauty-supply shop Ulta. When I went to Ulta to buy Magic Molecule, however, the person I asked for help had no idea what I was talking about. "What *is* this stuff?" she asked when she found the bottles, encased in slick, vague packaging. The label proclaims it "The Solution for All Skin Types" and encourages you to use it as often as needed. If I didn't already know about hypochlorous acid, my skepticism radar would have been on highest alert.

> Lots of things made by the body are manufactured and sold as serums, pills and powders. I might have dismissed hypochlorous acid as just another snake oil.

But it’s not just the beauty industry showing new interest in HOCl. Research into medical uses for hypochlorous acid has expanded as well. Before the pandemic, it was known that low levels of hypochlorous acid showed some promise in reducing the symptoms of viral and bacterial infections in nasal epithelial cells, but it was unclear how well people would tolerate HOCl administered straight up the nose as an irrigation or a spray. COVID led to some novel investigations.

At one hospital in Reading, Pa., for example, 74 COVID-positive patients, all of whom were unvaccinated, completed an experimental course of treatment that involved using a neti pot to rinse their nose with a hypochlorous acid solution for 10 days. Participants used Vashe Wound Solution, a hypochlorous acid that is safely used to treat wounds on skin or eyes and in the mouth. Although the author of the study acknowledged several limitations (for example, its small sample size and the lack of follow-up swabbing), it’s notable that none of the participants, who started the treatment within 72 hours of testing positive, required mechanical ventilation in the hospital. The reported adverse reactions were mild—a sensation of nasal burning, a nosebleed that stopped on its own—and the researcher suggested this application would be safe and effective, albeit one that requires more investigation.

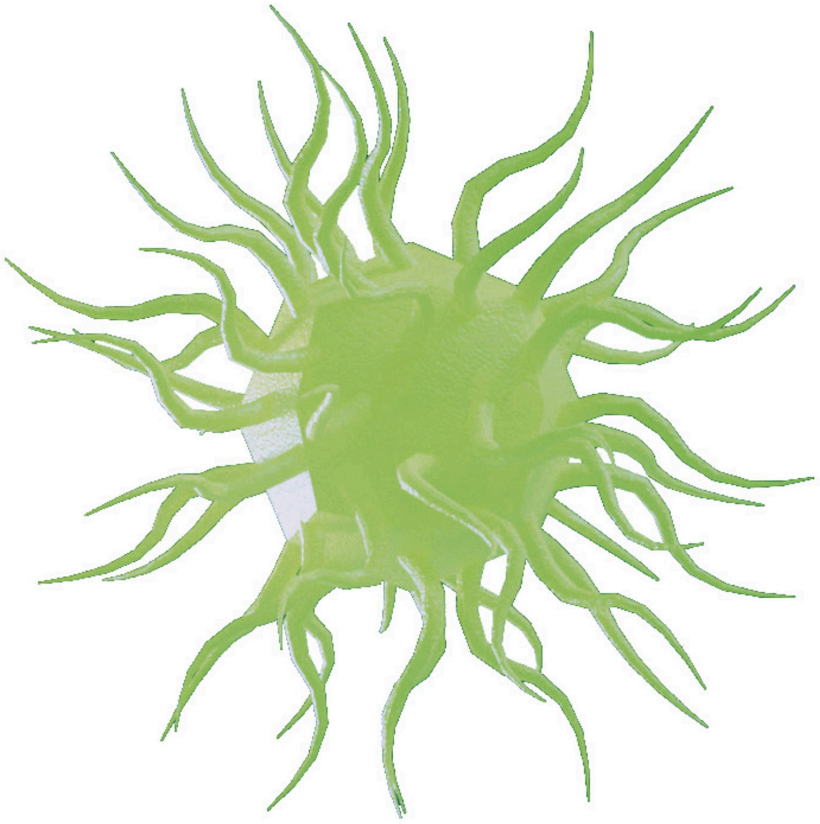
Other studies have since shown hypochlorous acid to be effective in reducing symptoms in a range of upper respiratory infections—and, more important, that it does not cause adverse effects. In Europe, Sentinox, an over-the-counter nasal spray containing a low concentration of HOCl (0.005 percent), is already certified as a medical device to reduce the risk of infection from viruses and bacteria, including SARS-CoV-2, by lowering the microbial load in the nose. In a randomized, controlled trial published in 2022, researchers used Sentinox on people with COVID and reported good outcomes with no evidence of safety concerns. “These promising results,” the authors wrote, “support future larger-scale clinical studies in order to assess whether the [Sentinox] spray is

also effective in the primary prevention of both symptomatic and asymptomatic SARS-CoV-2, influenza, RSV [respiratory syncytial virus], and other acute respiratory infections in the at-risk population." More work is needed to explore whether HOCl might have the potential to stop the spread of viruses from person to person.

Over the winter, my relationship with hypochlorous acid was like the gag in the 2002 movie *My Big Fat Greek Wedding* where the grandfather sprays Windex on everything as if it's a panacea. I sprayed down my phone case, sink faucets, toothbrush bristles and car steering wheel. I spritzed my face, hands and water bottle multiple times during workouts at the gym. After returning from the grocery store, I showered my bananas, limes, avocados and leafy herbs in the stuff. At a restaurant, I watched a server deliver my drink by holding the rim of my glass, so out came the bottle. I refrained from spraying my friend's toddler as I anxiously tracked his germy behavior while he moved across a carpeted airport floor.

When my seatmate on a crowded train coughed the entire ride, I lifted my mask and sprayed HOCl directly up my nose; for good measure, I also soaked my eyes.

Here's what happened: I got sick with type A influenza. My husband got it first, and I didn't try to avoid the inevitable. Just after recovering from the flu, I picked up COVID at a large family gathering. Given the nature of airborne respiratory viruses, these events didn't sour me on HOCl. I was diligent about spritzing myself and objects of potential exposure during travel, but it's not like I was excusing myself from dinner conversations to take a huff of the stuff. Without constant hypervigilance and social isolation, your time comes when your times comes. I can't live in a fog of aerosolized HOCl even if part of me wants to.



Richard Borge

As of this writing, I have not been sickened by norovirus, and I'd like to believe my judicious use of HOCl has something to do with that. If more people were aware of this molecule, maybe they would swap their Purell bottles and Clorox bleach for a more effective, safer option. (One product called a "norovirus cleanup kit" contains hypochlorous acid.)

One thing I hope we've learned from the early days of the COVID pandemic is that stopping the spread of infectious illnesses requires a collective effort. Hypochlorous acid has been shown to work against avian influenza. If bird flu becomes the next pandemic, HOCl could be one potentially effective mode of virus control that's easily available and cheap to access. Fogging machines could be used to clean surfaces and objects in medical settings, for example. (Fogging people with hypochlorous acid, which was done in Japan in 2020, for instance, is not known to be effective.)

But something about hypochlorous acid as a new product at a beauty store makes me uneasy. Although some of the products sold by recently established companies have been cleared by the FDA, many are not regulated. Notably, few of these products are specifically marketed as hand sanitizers, at least in the U.S. (A U.K. company does make a hypochlorous acid sanitizing hand gel approved by European regulatory agencies.) But if the efficacy of the product depends on its long-term stability, how much can you trust a bottle that's lived in your car for six months?

So-called miracle products abound on the Internet. Lots of things made naturally by the body are manufactured, bottled and sold as serums, pills and powders. Hypochlorous acid sprays now show up in my social feeds, promoted by influencers gushing about their skin-rejuvenating properties. Some of the products I've seen use specialty salts (truly unnecessary) and charge significantly more for the purported luxury. If I hadn't first encountered this disinfectant in academic literature, I might have scrolled right past these ads, dismissing hypochlorous acid as just another snake oil sold to exploit people's fears.

Hypochlorous acid might go through rigorous regulatory channels if it's pursued as an intranasal spray that prevents infection by killing viruses before they get into the lungs. Until then, I'll be discreet any time I spray hypochlorous acid up my nose, not because I'm worried this off-label use is harming me—the biggest risk is that I'm irrigating with very expensive saline—but because I think back to President Donald Trump's infamously cringey April 2020 press conference where he suggested possible COVID treatments. "And then I see the disinfectant where it knocks [SARS-CoV-2] out in a minute, one minute," Trump said. "Is there a way we can do something like that by injection inside or almost a cleaning, because you see it gets in the lungs, and it does a tremendous number on the lungs."

Trump was rightly skewered by experts (and many others) for promoting dangerous advice. It goes without saying that bleach, the disinfectant in question, should never be injected into your body. But behind Trump's misinterpretation of whatever medical information had been shared with him prior to that press conference was the seed of an idea: What if a disinfectant could do a type of cleaning, as it were, knocking out virus particles in less than a minute? With norovirus still circulating and the possibility of a bird flu spillover, the potential uses of hypochlorous acid might be worth a closer look.

Jen Schwartz is a senior features editor at *Scientific American*. She produces stories and special projects about how society is adapting—or not—to a rapidly changing world.

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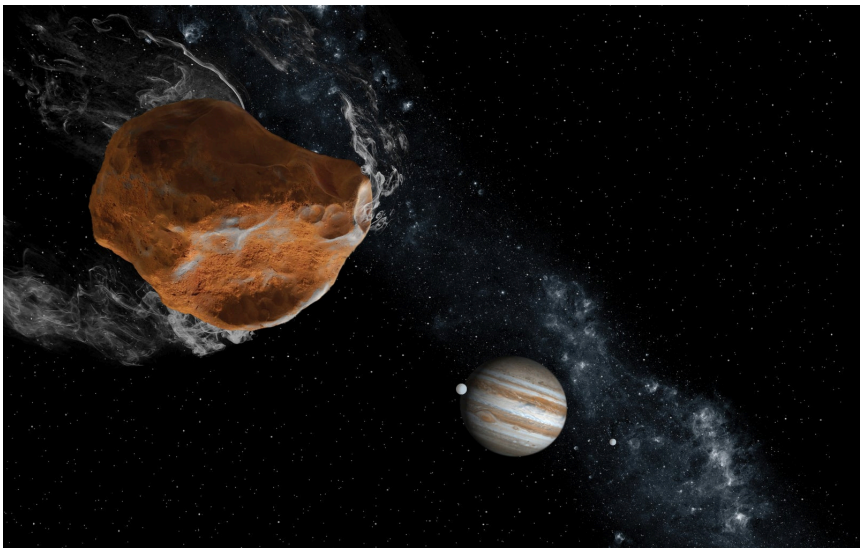
https://www.scientificamerican.com/article/hypochlorous-acid-is-trending-in-skin-care-and-cleaning-but-does-it-work

Mysterious Dark Comets Puzzle Astronomers

A group of comets with unexplained movements presents a quandary

By Robin George Andrews edited by Clara Moskowitz



Ron Miller

Davide Farnocchia hunts down and tracks asteroids, and several years ago he saw something he couldn’t explain. Farnocchia works at NASA’s Center for Near-Earth Object Studies in California. Using software programs he helped to build, he follows all the known asteroids and comets zipping about close to the planet. He’s a cartographer working in four dimensions. “Our job is to predict how things move in space,” he says. “So if there’s something novel or unexpected, that’s where the advance in the field lies for us.”

In 2016 Farnocchia saw something truly unusual: an asteroid, known as 2003 RM, that was wandering about seemingly with a mind of its own. Its orbit around the sun had shifted in a way gravitational effects couldn’t account for. He even took into consideration the small nudge that sunlight imparts to space rocks, and the asteroid’s orbit still didn’t match expectations.

“Something else is going on,” Farnocchia thought at the time. But what? Something was giving that asteroid a push, but there was no evidence of any rocketlike thrust. He was as puzzled as he was thrilled. “When things don’t behave the way you expect, that means there is something exciting down the road.”

Farnocchia and his colleagues spent some time ruminating on this autonomously moving asteroid, wary of making too big a deal of it. But in 2017, before they had a chance to come to any firm conclusions, they were interrupted by a messenger from another star. That October, for the very first time, an interstellar object was caught diving into and then scarpering away from our solar system. As it left, it accelerated dramatically—and, as with 2003 RM, nobody caught any sign of propulsion powering that acceleration.

This interstellar interloper, named ‘Oumuamua, was the subject of a scientific and media frenzy at the time—it was even suggested (without compelling evidence) that the object was an alien spacecraft. But this pandemonium overshadowed its peculiar similarity to 2003 RM and 13 other celestial oddballs that scientists have since found careening through our solar system.

“These objects really look like asteroids in the images,” Farnocchia says. “But their motion is more similar to that of comets.” They act as if jets formed by ice turning into vapor are pushing them around. But to date, no evidence of any such jets has been found.

“This cannot be just random,” says Darryl Seligman, a planetary scientist at Michigan State University. “There’s got to be something going on with these accelerations.” Because the source of their propulsion cannot be seen, Seligman has given these 14 solar system oddities a rather catchy name: dark comets.

Solving the riddle of these dark comets will do more than scratch an astronomical itch. If there is a family of stealthy comets in the solar system, then perhaps they delivered water to the inner solar

system long ago. “We don’t know where Earth’s oceans came from,” Seligman says. “That’s one of the main reasons to study comets. How did we get here?” And if these objects are moving erratically, their flight paths need to be fully understood—just in case any of them eventually try to crash into our planet.

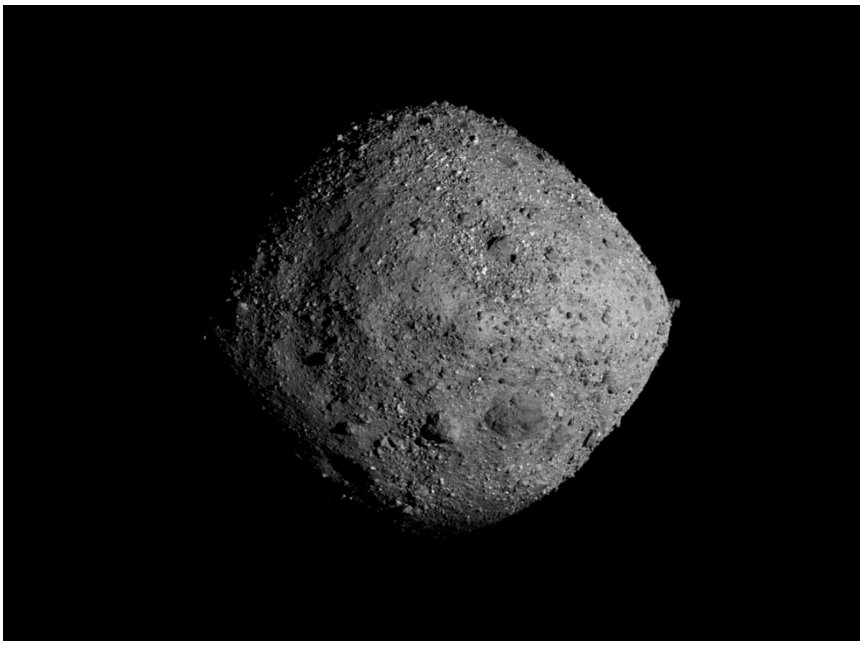
“Comets are already by themselves weird objects,” says Federica Spoto, an asteroid dynamics researcher at the Center for Astrophysics | Harvard & Smithsonian. The recent surprise of dark comets implies there’s even more about comets in general that we don’t understand. “We didn’t know they were there; we didn’t know the solar system worked that way,” Spoto says.

Unlike many cosmic detective stories, this one may quickly yield revelations. With two powerful telescopes poised to offer help, scientists hope to zoom in on these strange objects and perhaps detect cometlike outgassing for the first time. And, thanks to a stroke of sheer luck, a Japanese spacecraft whose primary mission has already been completed is on its way to visit a dark comet up close. “We will get the answers to what’s going on,” Seligman says.

The motions of asteroids—rocky debris left over from the formation of the solar system—aren’t dictated only by the gravitational pull of the sun and other planets. Sunlight also plays a role in steering them.

As the particles of sunlight, photons, hit a space rock, they exert a small push on it over time. It’s a noticeable but minor effect. “The pressure of just sunlight bouncing off you is not that large; otherwise we’d all be blown over every time it was a sunny day,” says Alan Fitzsimmons, an astrophysicist at Queen’s University Belfast. Then there is the Yarkovsky effect. Photons get absorbed by the sunward side of a rotating asteroid, heating that surface up. When the warmed surface rolls to the shadow side, it cools down and reemits that radiation, which acts as a minithruster to push it.

In 2016 Farnocchia and some of his colleagues were looking for evidence of the Yarkovsky effect in a catalog of near-Earth asteroids. Their report notes that several of these asteroids seemed to have nongravitational accelerations that couldn’t be explained even when the scientists invoked the shuffling effects of sunlight. They expected that most of these spurious detections would be accounted for by errors in the observations and that the orbits would look normal after correction.



The Japanese Hayabusa2 probe visited the asteroid Ryugu in 2018. It's now on an extended mission to survey more asteroids, including a dark comet.
JAXA

But one of the asteroids steadfastly refused to play ball. “Something weird was going on with 2003 RM,” Seligman says. It was acting as if it were an icy comet. Erratic comet movements are typically easy to explain. “There is ice on the surface of the comet, and when the comet gets close enough to the sun, that ice starts sublimating, and that gives comets a little push,” Farnocchia says.

Cometary outgassing tends to be invisible; it can be viewed only with special telescopic filters. But the dust jettisoned off a comet as it hisses and splutters is highly visible. Even just a kilogram of dust, with each grain no wider than one thousandth of a millimeter, is easily detected: it spreads out into a very thin but expansive disk

that enthusiastically scatters starlight. “You can see dust at any wavelength,” Fitzsimmons says.

But 2003 RM looked like a speck of light. There was no gas-and-dust coma around it; there was no tail. From afar it simply looked like an asteroid.

That didn’t mean it wasn’t concealing a supply of vaporizing ice. “There’s this growing recognition that asteroids and comets are end-members of a spectrum of bodies,” says Steve Desch, an astrophysicist at Arizona State University. And in the past few decades hybrids have been discovered. Some asteroids are suffused with water and ice.

Comets like to hang out beyond Neptune, where various substances —water, ammonia, carbon dioxide and monoxide—can remain frozen. But somehow, despite being considerably closer to the warm glow of the sun, several objects with comas and dust tails have been found meandering through the asteroid belt between Mars and Jupiter, as if they got lost while on vacation. Astronomers call them main belt comets.

> A Japanese spacecraft is already on the way to visit a dark comet—and the commanders of that mission didn’t even realize it until recently.

With all this in mind, it wouldn’t be surprising if 2003 RM outwardly resembled an asteroid but occasionally displayed cometary activity. “The problem is nobody’s ever reported any coma or dust from it,” Fitzsimmons says. Seligman, Farnocchia and their colleagues later wrote a paper with a parablelike title: “The Asteroid That Wanted to Be a Comet.” They were, for some time, befuddled.

And that’s when ‘Oumuamua crashed the party.

On September 9, 2017, a voyager from a distant realm was making its closest flyby of a yellowish, fairly milquetoast star within the orbit of a small, cratered, rocky world. This sojourner went unnoticed by the nearly eight billion inhabitants of the nearby blue-green planet named Earth—at least until October 19, just a few days after it passed a mere 24 million kilometers above their heads.

Almost immediately after a telescope in Hawaii spotted the object, astronomers around the world scrambled to track it—and quickly found themselves awed. This rock was on an extremely arched trajectory that indicated it came not from within the solar system but from far outside it. Follow-up observations revealed that it was shaped like either a pancake or a cigar and that it was fairly shiny. But it was the fact that it sped up as it left the solar system—faster than could be explained by the gravitational-slingshot shove it received as it swung around the sun—that truly stunned the astronomical community.

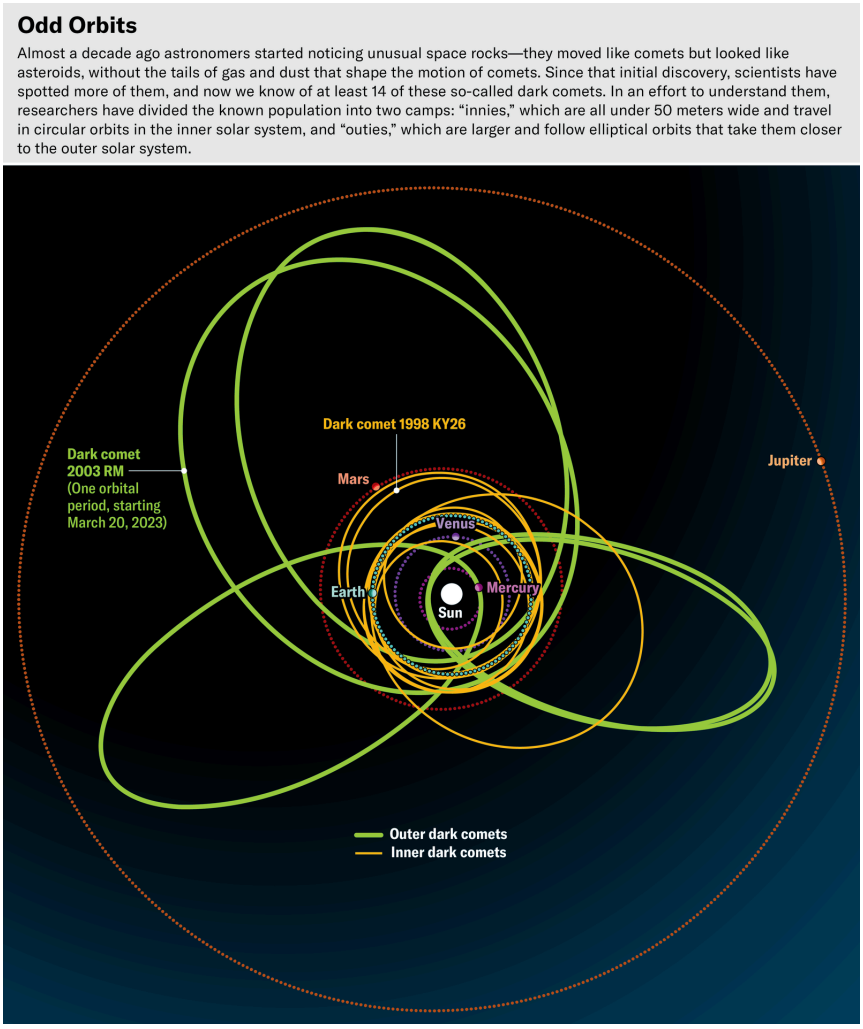
Because the object was spotted while it was already making its escape, astronomers had only a limited time to gather observations. A shiny object that was engaging in nongravitational acceleration was, they thought, probably a comet. But this acceleration was far stronger than anyone would have expected from a typical comet—and, despite hasty efforts to find it, they saw no evidence of any cometary outgassing or expelled dust.

"It reminded everyone so much of *Rendezvous with Rama*," Desch says, referring to a 1973 science-fiction novel by Arthur C. Clarke in which an enigmatic cylindrical spacecraft passes through the solar system. The 2017 object was sometimes casually referred to as Rama before it was officially given a Hawaiian name: *ʻOumuamua*, meaning "a messenger from afar arriving first."

Certainly it was fun to think about the object, with its odd shape and invisible propulsion, as an alien spaceship, but most scientists didn't take the idea seriously. Infamously, Harvard University

astrophysicist Avi Loeb argued that it could be an extraterrestrial reconnaissance probe powered by solar radiation pressure. Yet no convincing evidence exists to support that claim, one that astronomers—including Desch—have comprehensively torpedoed. “In the past, people would not call on spaceships. They would call on dragons or fairies,” says Olivier Hainaut, an astronomer at the European Southern Observatory. “What is more likely: a slightly weird comet that behaves a little like those we know or a spacecraft?”

To be fair, the source of ‘Oumuamua’s nongravitational acceleration during its exodus remains unknown. The object has left our galactic neighborhood forever, and the few observations of it offer only clues, not certainty. Some have suggested that it was a piece of a planet like Pluto and that effervescing nitrogen ice gave it its rocketlike boost. Others wondered whether it was a sublimating hydrogen iceberg instead.



Jen Christiansen, Source: "Two Distinct Populations of Dark Comets Delineated by Orbits and Sizes," by Darryl Z. Seligman et al., in *PNAS*, Vol. 121; December 9, 2024 (*orbital reference*)

In 2023 Seligman and his colleagues speculated in a paper that ‘Oumuamua might be a water-ice comet after all. Maybe when it gets zapped with cosmic rays, water particles break down into hydrogen and oxygen, which get trapped in pockets of shapeshifting ice. When bathed in sunlight, the ice releases that hydrogen gas, propelling the otherwise typical icy comet at breakneck speeds.

There is a small chance that ‘Oumuamua wasn’t behaving like a comet at all. Pressure from solar radiation could be pushing it away from the sun, but that would work only if the object has a very specific shape: “a ginormous snowflake-type thing,” Seligman says —kind of like an ultralow-density icy sail. But, he says, it is probably a weird comet.

“‘Oumuamua was interesting because it was the first interstellar object to be discovered,” says Farnocchia, who also studied it closely. But, crucially, for those also pondering 2003 RM’s shifty movements, it rang a bell. Both objects moved in a cometlike way, probably through some kind of ice vaporization that couldn’t be detected. Although ‘Oumuamua’s unusual shape and variety of exotic ice possibilities made it more of a cousin to 2003 RM than a sibling, its presence did suggest that 2003 RM was probably not alone in our solar system.

Farnocchia and his team quickly scanned the solar system for signs of any other stealthy, cometlike objects. In 2023 Seligman, Farnocchia, Hainaut, and others announced a new discovery—well, six, actually. They had identified half a dozen additional 2003 RM–like objects, each with inexplicable nongravitational accelerations, each lacking any evidence of cometary activity, even when the most eagle-eyed telescopes in the world were pointed at them.

The hunt was on to find even more of them, and it didn’t take long: by 2024 the team had found seven more, bringing the total to 14. And that’s when things got really weird.

As before, the effects of sunlight on these new objects couldn’t explain their anomalous accelerations. And, just as the scientists had expected, they could find no sign of any dust being jettisoned by any of these 14 rocks. Other astronomers not involved with the study can find no fault in the team’s analyses. “They’re really good at this,” Fitzsimmons says. “There are no mistakes in this work.”

Dust blasted off the surface of comets is, remember, very easy to see. That fact implies that when these objects are cooked by the sun, and their ices vaporize, they “are only emitting puffs, like a little squirt of air,” says Meg Schwamb, a planetary astronomer at Queen’s University Belfast. But it was frustrating that no one could see any of that dust.

By this point, though, Seligman had noticed something exceedingly odd about these dark comets: they could be divided into two distinct families. One family, the outer dark comets—let's call them outies—seemed more reflective and larger, on the order of hundreds of meters in length or longer. Their family name comes from the fact that they linger closer to Jupiter and the outer solar system. Their elliptical orbits even resemble those of Jupiter-family comets; these objects orbit the sun in less than 20 years and were originally sourced from the Kuiper belt, a torus-shaped band of icy orbs beyond Neptune. Asteroid 2003 RM is one such outie.

Then we have the inner dark comets, or innies. These are smaller—all 50 meters or less in diameter—and have circular orbits that stick within the inner solar system. An object called 1998 KY26, which may be just 10 meters across, is an example of an innie.

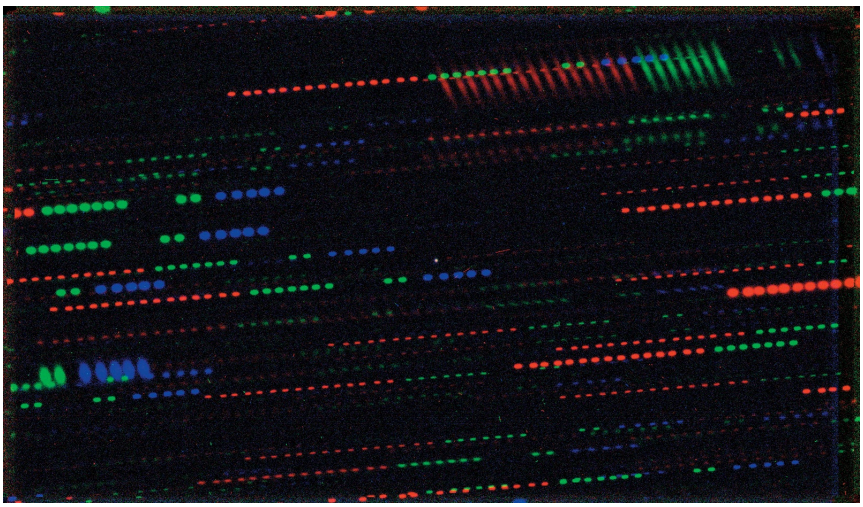
The team suspects the outies are easier to explain. These shinier objects with cometlike orbits are probably icy comets with limited —and therefore very difficult-to-detect—outgassing and dust release. If so, they may provide a new answer to a long-standing question. "How do comets die?" Fitzsimmons asks. "We know some of them spectacularly fall apart, break apart," particularly if they do an Icarus and fly too close to the sun. But the seemingly minimal cometary activity of the outies lends support to another mechanism: suffocation.

If, as outies approach the sun, their vaporizing water ice releases enough buried dust into space, a lot of it may tumble back down onto the comet's icy nucleus. If the ice is continually smothered by dust, then it will be increasingly insulated from the sun's glare. After some time only small patches will, very briefly, get vaporized and release puffs into space. Perhaps eventually none of the ice will be exposed at all. "They're covering themselves in a blanket of dust and saying, 'That's it, I've given up being a comet. I want to be an asteroid now,'" Fitzsimmons says.

The innies are more troublesome to explain—which makes them more beguiling. One conundrum is that if they spend all their time in the inner solar system being frazzled by the sun, how can they have any ice left to fuel their sporadic accelerations? But “the real strange thing is their size,” Fitzsimmons says. “We have never seen an active comet nucleus smaller than a few hundred meters across.” A minuscule nucleus is extremely vulnerable to annihilation, either via heating or by spinning itself up into a self-destructive pirouette. And yet there the innies are.

Seligman isn’t sure how closely the innies and outies may be related. One possibility is that the outies sometimes tumble into the inner solar system, and the innies are a late-stage version of them that’s racing toward a dehydrated demise. Alternatively, the innies could be main-belt comets—which do have observable comas and tails—that have been scorched for such a long time that they’re almost completely desiccated, rendering them unable to showcase almost any cometary activity.

Having 14 of these dark comets to study is a boon to the team. The collection still leaves them with more questions than unequivocal answers, but by this point the wider implications of dark comets are starting to become clear.



The faint white dot (*center*) surrounded by star trails in this image by the Very Large Telescope and the Gemini South Telescope is 'Oumuamua, an interstellar asteroid that originated beyond the solar system.
ESO/K. Meech et al.

Models suggest a small fraction of Earth's water was made within the planet and erupted onto the surface via volcanism. Where did the rest come from? "The obvious candidate is comets," Hainaut says. But because comets spend most of their time in the Kuiper belt or the considerably more distant Oort cloud, they seem too far away to have done the job. Dark comets might offer a closer source. "It's very easy to bring stuff from the asteroid belt to Earth," Hainaut says—and main-belt comets, along with the inner dark comets, handily fit the bill.

The existence of dark comets might also have ramifications for planetary defense, the science of preventing dangerously large asteroids and comets from crashing into Earth. One of Farnocchia's primary occupations as a member of NASA's Center for Near-Earth Object Studies is to find potentially hazardous asteroids before they find us—so it's in his (and everyone's) interest that we know how to calculate the slightly less predictable orbits of dark comets.

In other words, if you find a larger near-Earth asteroid that nobody has identified before, that's a great start. "But if you don't know where it's going to be, that won't matter," Seligman says.

Farnocchia, a planetary defense veteran, isn't too concerned. The automated software that's designed to both detect and then precisely track the motions of near-Earth asteroids (and comets) far into the future may not yet fully account for the novelty of dark comet–style accelerations. But on the scale of a human lifetime, "you'd still be able to connect the dots," he says.

Dividing the dark comets into two families in 2024 was a marked step forward, but the scientists hunting them down were still left furrowing their brows in confusion. "What is going on?" Farnocchia asks. What are these objects, and why can't we spy any of their jettisoned dust?

Although extremely powerful optical telescopes have so far failed the researchers, two others will soon be able to aid their quest. The first is the Vera C. Rubin Observatory, a gigantic, wide-eyed digital camera being assembled on a mountain ridge in Chile. It will come online later this year, and within just a few months it will find millions of new asteroids and plenty of comets—almost certainly increasing the known dark comet population and giving the team more of these aberrations to study.

The second, if the researchers can convince the powers that be to give them some time to use it, is the James Webb Space Telescope (JWST). Its infrared scope can see things other observatories cannot—including the normally invisible water-vapor outgassing of comets. “JWST is really the only telescope we could use to measure their outgassing coma,” says Aster Taylor, a Ph.D. student of planetary astrophysics at the University of Michigan and a dark comet aficionado.

In 2023 JWST confirmed the presence of water vapor around a main-belt comet for the first time. The dust presumably shooting off dark comets may be elusive, but the researchers could use JWST to look for outgassing instead. “If they find water emission, that really does nail it,” Fitzsimmons says—case closed.

Competition for JWST is fierce, and the team’s initial dark comet–surveying proposal was rejected. The scientists have a new JWST proposal under consideration, “so we hope we will get that this time,” Seligman says. Even if they don’t see any outgassing, they can still use the space telescope to get an idea of the mineral content on the dark comets’ surfaces, which may reveal the presence of ice.

What’s got the dark comet hunters particularly animated, however, is that a Japanese spacecraft is already on the way to visit a dark comet—and the commanders of that deep space mission didn’t even realize it until very recently.

Japan's Hayabusa2 mission is one of the all-time asteroid-hunting greats. Its goal was to retrieve a pristine sample of a carbon-rich asteroid named Ryugu and bring it to Earth so cosmochemists could learn whether ancient asteroids contained the building blocks of both planets and biology. It succeeded beyond all expectations. In 2018 it reached Ryugu. The following year it fired a bullet at the asteroid to excavate a crater, exposing buried primeval matter, before flying down toward it and scooping up some of those grains.

After safely delivering that invaluable treasure to Earth in 2020, Hayabusa2 flew back into space—and its extended mission began. This time it was taking on a planetary defense role. It was now named Hayabusa2# (the # indicates "sharp," as in musical notation; here it stands for Small Hazardous Asteroid Reconnaissance Probe). It is now flying to two nearby asteroids that are smaller than Ryugu but still in the size range of space rocks that could imperil Earth, just to check them out. It will zip by the first asteroid, named Torifune, in July 2026, and in 2031 it will rendezvous with a far smaller object—1998 KY26.

That's right: it's one of the inner dark comets. "I'm surprised," says Yuichi Tsuda, project manager of Japan's Hayabusa2 mission. The rock was originally chosen because it's small, it's spinning incredibly rapidly, and, unlike larger asteroids, which tend to be rubble piles, it's just a single rocky shard. "We thought it's very important to study for planetary defense," Tsuda says. When it was chosen as a target several years ago, his team hadn't come across any of the research into dark comets.

In 2023, desperate to collect more information about his rising tally of dark comets, Seligman searched online for more information about each of them. When he looked up 1998 KY26, a torrent of academic papers flooded his screen. "When I put it together, I was like, 'Oh, wow!'" he says, laughing. "It was super lucky—serendipitous. It was like the cherry on top." Finally, a dark comet is about to be brought into the light.

Tsuda and his team are still working out what to do when the spacecraft reaches 1998 KY26. They might try to orbit the dark comet and scan its surface for any cometlike ices and minerals. They could use their remaining bullet to blast a crater in its side, revealing its internal composition. Hayabusa2# might even end its extended mission by attempting a risky landing on the frantically spinning rock.

Whatever the choice in the end, the dark comet team can't believe its good fortune. "Our Japanese friends are going to have lots of fun," Hainaut says.

For the time being, dark comets will remain mysterious. "It's hard to explain how they exist in the first place," Fitzsimmons says. "That's just Mother Nature being cleverer than we are. That's what astronomy's all about, figuring out how Mother Nature does stuff. How did that get there?"

There is a chance that all this work will amount to little. "[What] if observations come back, and we don't see anything?" Seligman wonders—no outgassing, no dust, but persistent cometlike accelerations. "What are we going to think?" Or perhaps by 2031 the Rubin Observatory will have found dozens of other dark comets, JWST will have found crystal-clear evidence of outgassing, other telescopes will have finally detected telltale dust plumes, and Hayabusa2# will have made a dark comet its final resting place among the stars.

It's likely that the dark comet team will soon have answers, and our solar system will become just a little bit more predictable. "I don't think I've emotionally prepared myself for that," Seligman says. He lets out a sigh. "It's fun for it to be a mystery."

Robin George Andrews is a volcanologist and science writer based in London. His most recent book is *How To Kill An Asteroid* (W.W. Norton, 2024). Follow him on X @SquigglyVolcano

https://www.scientificamerican.com/article/mysterious-dark-comets-could-unlock-solar-system-secrets

The Hidden Social Lives of Male African Elephants

Long thought to be loners, male African elephants turn out to have surprisingly rich social lives

By Caitlin O'Connell edited by Kate Wong

Young male elephant (*right*) greets an older male (*left*).
Caitlin O'Connell and Tim Rodwell

I woke up in the research tower to a soft exhale and then a trickle of water at the waterhole below. The full moon hung low and dim in the west. I squinted at my watch. It was 4 A.M. I wondered which of my elephant study subjects had come to drink at this hour. Elephants are creatures of habit, and they typically don’t show up here at the Mushara waterhole in Namibia’s Etosha National Park until at least 11 A.M. But the full moon does funny things to elephant movements.

I rolled over in my sleeping bag to look out at the visitors. Two bulls stood at the source of the spring, drinking quietly. The older one was facing sideways, and the younger one had his back toward me. Focusing my binoculars on the edges of their ears, I could see a

telltale tab on the left ear of the older one and two sharp cuts on the right ear of the younger one. It was Abe and Andries.

My team and I had been following the older bull, Abe, since 2004 and Andries since 2011. Abe hadn’t visited Mushara for the entire 2024 field season, and here he was in all his glory, his tusks having grown out nicely after breaking a few years ago. I was glad to see him, not only because I enjoyed observing his endearing patience with younger males but also because he was one of my most important study subjects.

Abe was an integral member of a social group whose behavior I had been focused on documenting for years. African elephants have matriarchal societies, in which elder females lead families made up of their female relatives and young to water, food and safety. Most of what we know about elephant social behavior has come from studies of these female-led family groups. Males, in contrast, leave their family group as they reach adolescence and go off to live as bachelors. Historically, little research was conducted on the social dynamics of adult male elephants because they were thought to be largely solitary. It seemed safe to assume their social lives were simple, with none of the complex rules and rituals seen in the family groups.

When young male elephants visit the waterhole with their families, they get to interact with bachelor males and learn who they can trust when the time comes to set out on their own.
Caitlin O'Connell and Tim Rodwell

But research that I and other scientists have been carrying out is finally starting to fill this gap in our understanding of elephant behavior. Our long-term observations of Abe and the other males

who have visited Mushara over the past two decades reveal that male elephant societies have incredibly intricate rules, rituals and hierarchies of their own.

Male elephants, we are learning, are sensitive social animals that crave companionship and need emotional support. Their experiences of growing up parallel those of human males, who undergo similar social changes and pressures as they enter the adult world—from backslapping in the bar, to defending another's honor by taking on a bully, to being best friends forever. Having a social network of other trusted males may be important for navigating the transition to adulthood.

These findings indicate that this highly intelligent species is even more socially complex than we previously understood it to be—and could inform vital efforts to manage and protect these animals in the wild and in captivity.

One of our most exciting discoveries concerns vocal communication. Researchers have long known that female African elephants use vocalizations to coordinate group behavior. In family groups gathered at a water source, a dominant female, usually the matriarch, will step away from the water, align herself toward the direction she wants to leave in and then rumble a call to action —"Let's go!"

It's understandable why families would engage in this behavior. Coordinating a group of 20 to 40 or more elephants isn't a simple task. Using a vocal tool to call the group into line is well documented in other species, too. Among gorillas, for example, one ape's grunt triggers another to grunt, and another and another, until consensus is reached and all leave the area together. The same is true of wild dogs, who sneeze to reach consensus about departure. But whether male elephants, with their looser group structure, engaged in similar vocal coordination was unclear.

I suspected based on a handful of observations that the male elephants were indeed communicating in this way, but I needed a larger sample to prove the pattern was real. The male elephants that congregate at Mushara tend to be most vocal at night, which also happens to be when conditions are best for recording their sounds. And so I found myself working the late shift during our field seasons, timing my observation sessions to when the bachelors were chattiest.

Recently my collaborators and I published a paper containing the fruits of this labor. We were able to show that when a group of male associates leaves the waterhole, one of the core members of the group flaps his ears gently while emitting a long, low rumble—the “let’s go” signal. In turn, the others respond with their own rumble while following the instigator away from the water, each waiting for another to finish their call before contributing their own say in the matter. The paper marks the first time such coordination has been documented in male elephants, as well as the first time vocalizations have been shown to trigger action within male groups.

When I first witnessed groups of bonded males engaging in this kind of vocal ritual, I got really intrigued. Why would these males want to leave together? Unlike the family groups, in which the dominant females who determine the group’s movements are acting in the interests of their close relatives, male elephants have traditionally dispersed far from their natal group. This arrangement meant that they were often not related to the other males with whom they associated.

Bonded males arrive at the waterhole together using vocal coordination (*top*). Such groups also coordinate their departure this way. After a socially connected male initiates the "let's go" rumble, the rest of the group members take turns rumbling their assent as they walk away together (*bottom*). Caitlin O'Connell and Tim Rodwell

Leaving together implies they'll be sharing resources at their next destination. I had seen powerful older males shake full-grown

acacia trees to make the seed pods—a favorite food of elephants—shower down to the ground. On some of these occasions a younger bull or two came in to sample the spoils. Usually established group members would shove chancers away from the prized pods, but they tolerated ones who had arrived at the invitation of the older male. There had to be some advantage to older males inviting younger males to join them in their travels.

Why would older males want to share with younger associates when they didn't have to? What advantage was there in staying together? Could these males want the companionship even if it meant sharing? Did male elephants form even tighter-knit groups than previously thought? Our observations of vocal coordination among the Mushara males sparked many such questions. Studies of other aspects of their behavior have led to some answers.

To the untrained eye, the most obvious ritual exchange between male associates is what we call the greeting. A younger individual often initiates the greeting, placing the tip of his trunk either within or just at the entrance to the mouth of a buddy or an older male. The greeting is typically reciprocated—unless the recipient is very high-ranking. In that case, the gesture is more like a salute of one or more individuals to a general or a kiss of a royal's ring.

Beyond the greeting, the behind-the-scenes decorum in male engagement is so fine-tuned it's like the list of steps for having tea with the queen. We can look at the ritual of play for another example. For male elephants, play is important for building trust and developing skills needed to compete for mates later in life. Our data show that individuals of all ages within a bonded group of male elephants solicit play with other individuals in equal amounts. More often than not, however, younger elephants must wait until the older one initiates the play bout, regardless of which one solicited it.

Such conventions are hallmarks of a very sophisticated society. Each ritual helps to reinforce the rules of engagement within the group, thus strengthening bonds. This is all very much in keeping with what we already know about elephant intelligence, long-term memory, empathy and sense of self based on studies of the female-led family groups. What's new and surprising here is that we're documenting these group dynamics in males, who were long thought to be mostly solitary. And not only do we see rituals in these male groups, but the groups also engage in behaviors indicative of a hierarchical social structure.

In our study of vocal coordination triggering group action, we described, for the first time, a case of active leadership in male elephants. An active leader is one who solicits others to follow him and exerts social influence through means of dominance ranks, social position or experience. In contrast, passive leadership might occur when an older individual is followed by an uninvited youngster. In these situations, the older individual often signals his displeasure by turning around and shaking his head. This response usually deters unwanted companions, but it depends on how determined the younger one is.

My colleagues and I got our first inkling of male leadership in the Mushara social club back in 2004. A dominant bull we named Greg seemed to call the shots. Long conga lines of males of all ages and sizes followed Greg in and out of the waterhole. He was beloved by his underlings and either feared or revered by many of his contemporaries and elders. He led with a carrot-and-stick style—forgiving of the transgressions of youngsters but hard on his contemporaries.

Two males bond at the waterhole. Bachelor males of all ages benefit from socializing with other males. Such interactions can lead to lifelong companionship.
Caitlin O'Connell and Tim Rodwell

When Greg decided it was time to depart Mushara, he would stop drinking, turn in the direction he planned to go and invite the others to leave with a “let’s go” rumble. His message elicited synchronized, ritualized rumbles from the rest of the group. On occasion Greg would give some of the youngest ones a gentle shove to expedite any deliberations.

The simple act of inviting others to leave with him showed that Greg and males like him, who are socially connected, actually make an effort to keep the group together. This behavior is news because leadership in male social groups is not a given in mammals. Take the olive baboon, for example. A dominant male baboon has seemingly no interest in leading his underlings. His primary interest is in securing the best resources for himself, mates and food included. It's the female baboons who do the leading.

Over the years, as I observed Greg and the other males at the Mushara, I thought about why male elephants might come together in these groups and coordinate their actions. Forming coalitions could be one explanation. Ritualized vocal coordination could solidify and reinforce bonds the elephants needed to work together to intimidate or push off rival males. An unwanted individual could suddenly find himself facing a wall of imposing elephant ears, held up high like battle shields. It would be a lot easier to gain access to the best resources as a group than for an individual to defend them on his own. And considering that the Mushara waterhole was one of only three water points in the region, it was a vital resource to defend.

Despite this obvious benefit, I couldn't help wondering whether there were other factors in play. Perhaps there was a reproductive advantage for older males who adopted the emotionally needy underlings.

In a previous era, when elephants were free to roam in an environment unobstructed by fences built by humans, male elephants left their natal families during their coming-of-age testosterone spikes and were thought to settle far from their genetic line. This dispersal pattern maintained the diversity of the elephant gene pool, and it implied that males found socializing together were not related. But the realities of modern Africa are such that elephant movements are often impeded by human activity, and

young males can’t move as far away from their families as they might have in the past.

Older male Abe (*front*) and younger male (*back*) listen for the arrival of their companions.
Caitlin O'Connell and Tim Rodwell

This ecological shift increases the odds that a bachelor will encounter his male relatives on the landscape after dispersing from his natal group. If males within bonded groups were in fact related to one another, their genetic line would have a better chance of getting passed along if older males could help ensure that their relatives survive and reproduce.

Many species, such as mice, can smell related individuals and hence avoid inbreeding. It occurred to me that male elephants might have a similarly innate ability to recognize relatives. If so, a father elephant might be able to identify his offspring through olfactory cues and choose his companions accordingly. In fact, another recent study by my team indicates that male elephants track one another over space and time in a way that could be achieved only through olfaction and possibly vocalizations. We found evidence that males remotely monitor one another’s locations and move toward or away from other elephants depending on their social relationships. (Similarly, adult males find mates by listening

for the distinctive calls of estrus females and smelling olfactory cues in their urine.)

We are still studying the relatedness of individuals in these bachelor groups. Future findings may shift our understanding of whether, by associating in these groups, males are acting to maximize their ability to reproduce and pass their genes to the next generation. There may be additional factors to consider as well. Another advantage of keeping a group together is companionship. Younger males, who are still struggling to adjust socially to life outside a huge family, certainly benefit from older males who can model good behavior.

Older males may gain from this association, too. In another recent study we conducted on male elephant character, we showed that adult males profit psychologically from the companionship of younger males. We collected behavioral data from 34 individually known males at Mushara over a five-year period and found that the presence of young males in a group reduces aggression and increases affiliative, or friendly, behavior in older males. Male elephants of all ages need socialization just like any other social animal. They seek interaction and bonding from youngsters, contemporaries and elders they can look up to.

Given how important bonded groups are to elephants, I never would have expected that the structure of male elephant society was vulnerable to collapse. But after our 2011 fieldwork season at Mushara, Greg disappeared. I anticipated a scramble for power. Instead we witnessed a complete destabilization of the social club. Greg’s absence ushered in an era of small factions; no one took up his leadership torch. Not even his best buddy, the well-respected Abe, stepped up.

Abe just didn’t seem to have the titanium stomach required to rule, which was understandable. Being at the top is a lot of work—always having to posture, appeasing the youngsters while signaling

dominance to one’s ever-watchful upwardly mobile contemporaries, facing the threat of being toppled by a potentially mortal blow at any moment. Yet somehow Greg was able to do it with surprisingly little stress, according to his cortisol profile, which we assessed by collecting and analyzing his feces over the years.

Young adult male Shaka, shown here back in 2011, now displays signs of active leadership and may one day become the leader of the social club at Mushara.
Caitlin O'Connell and Tim Rodwell

Some 14 years after Greg’s disappearance, the Mushara males remain leaderless. But there are prospects. Young adults Kelly and Shaka have shown signs of wanting to mentor the next generation. They have allowed younger males to explore their faces and tusks, place tentative trunks in their mouths and hang a trunk on their tusk. They have even permitted two youngsters to hang their trunks on their tusks, one on each side, while Kelly and Shaka try to drink.

I’d give anything to know what these young males are thinking in these moments of exploration and seeming admiration of the

grown-ups. Puberty is a traumatic period of uncertainty for these youngsters. For a male that has grown up within a tight-knit elephant family, it's a big social adjustment to live outside the family. He is not accustomed to isolation. Companionship is all he knows. I suspect that any ritual of connection would give a young male a sense of belonging—whether it be a secret handshake or tolerance from an elder. Acceptance goes a long way toward easing the transition to adulthood.

It takes a certain kind of male character to have patience with these youngsters—and to take up the mantle of leadership. He has to have all the right stuff. According to our recent character study, the right stuff seems to be a combination of self-confidence and a sense of decorum that gains the confidence of the group. Leaders tend to be the most socially integrated members of the group, not necessarily the most dominant.

After an older male allows young males to explore his face and body with their inquisitive trunks, the next sign that he has an interest in mentorship is the act of inviting these younger males to join him as he departs the waterhole. I can tell from the perky posture of the young males who receive such an invitation that they understand exactly what it means—that they have been accepted into the most important social club of their lives, where membership could last a lifetime.

I eagerly await these moments of active leadership. The more we understand about the complexities of male elephant society, the better we will be able to protect and manage this species. All our recent findings and the findings of others further speak to the social nature of male elephants. This work has implications for wild, captive and semicaptive males. For example, people who manage captive elephants might be able to improve their welfare by putting the males in mixed-age groups and organizing these groups around older males who have demonstrated leadership potential. Likewise, efforts to manage elephant populations in the wild ought to factor

in the importance of postreproductive bulls to coming-of-age males. Not only does their presence keep younger males, with their raging hormones, from becoming too aggressive, but they also contribute to the younger males' sense of belonging.

Now every time I hear a male "let's go" rumble exchange, I jump out of my sleeping bag and turn on the sound recorder and the night vision scope. I quickly document who is involved in the exchange —who initiated and who responded and when. These observations give me hope for a return to the good old days at Mushara, when the group thrived under Greg.

All too soon after Abe and Andries finally showed up at the waterhole last year, they set off again. As I watched them head south, Abe flapped his ears, and Earth's largest land animal emitted the lowest-frequency vocalization on the planet. It was the "let's go" rumble—the invitation to accompany him. It was the call that Abe had so often enjoyed responding to but rarely initiated himself. With a little pep in his stride, Andries answered the call to action with an equally long and low response.

I rolled over and tucked myself back into my sleeping bag for just a little while longer. In an hour the camp would be a buzz of activity to pack up and leave. The Mushara field season had ended, and I was grateful for Abe's appearance, even if only in the final hours of my stay. It gave me peace of mind to know he was still out there. I was also glad to see Shaka and Kelly, the next generation after Abe, offering new coming-of-age males safe harbor.

The sound of the "let's go" duet faded. I imagined Abe and Andries saying to each other, "If you go low, I'll go high!" as they harmonized and disappeared into the bush, bound for their next destination in good company.

Caitlin O'Connell is a behavioral ecologist at Stanford University's Center for Conservation Biology and Harvard University's Center for the Environment. Her research focuses on elephant behavior and communication. O'Connell's latest book is *Wild Rituals: 10 Lessons Animals Can Teach Us about Connection, Community, and Ourselves* (Chronicle Prism, 2021).

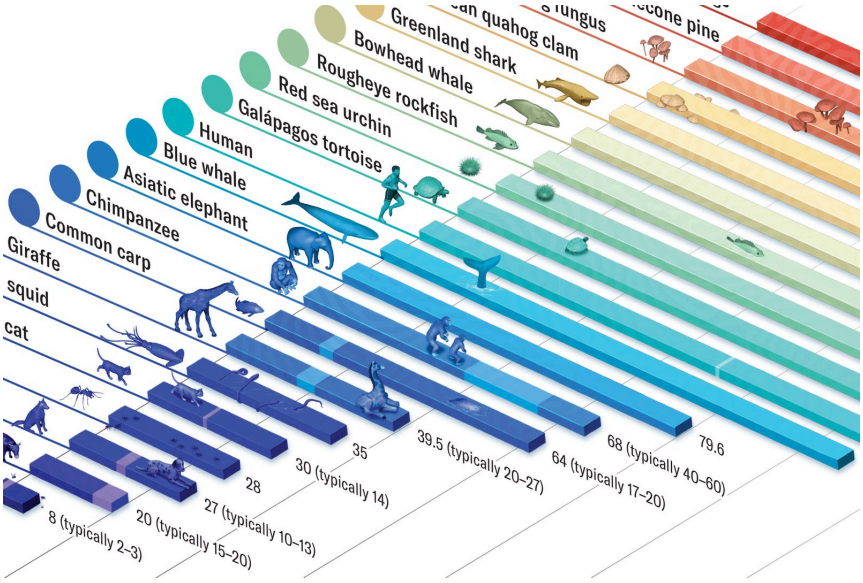
Aging

- **Why Some Animals Live for Only Days and Others Live for Thousands of Years**
  Scientists are studying why some species live so much longer than others

Why Some Animals Live for Only Days and Others Live for Thousands of Years

Scientists are studying why some species live so much longer than others

By Clara Moskowitz & Mark Belan edited by Jen Christiansen



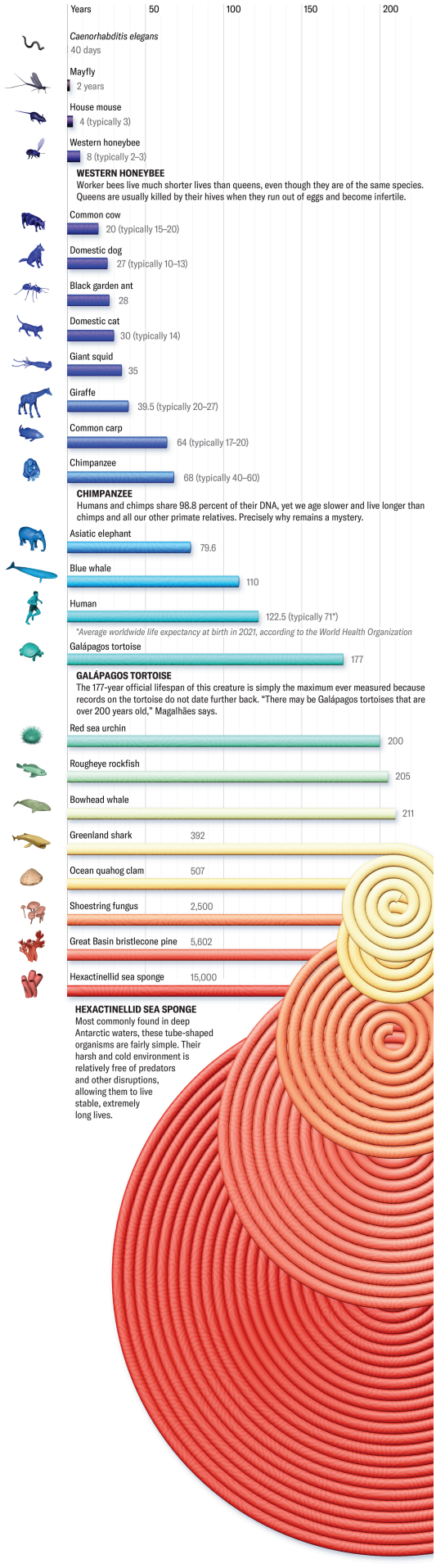
Mark Belan

Some species seem to live fast and die young. Others, though, “appear not to age,” says João Pedro de Magalhães, a molecular biologist at the University of Birmingham in England. He is project leader of the Human Ageing Genomic Resources program, which keeps the AnAge database of maximum animal lifespans. Some species of turtles, fishes and salamanders, for instance, don’t show any signs of degeneration or senescence as they grow older. If they didn’t die of predation, accidents or infectious disease, they could live extremely long lives, Magalhães says.

“It’s a biological mystery why some species age faster than others,” Magalhães says. “We still don’t understand well the mechanisms behind aging.” Species that face high predation usually evolve to

grow quickly and reach sexual maturity rapidly. Other creatures that don’t face pressure to reproduce early can age slowly: Greenland sharks, for instance (the top of their food chain), may take 150 years to reach sexual maturity.

DNA mutations are thought to play a role in determining lifespans, with longer-lived species tending to evolve better DNA-repair systems to help ward off cancer. Short-lived creatures, such as mice, don’t have these abilities, because in the wild they often die of predation before cancer becomes an issue. Laboratory-raised mice, however, have very high rates of cancer.


Years
50
100
150
200
Caenorhabditis elegans
40 days
Mayfly
2 years
House mouse
4 (typically 3)
Western honeybee
8 (typically 2–3)
WESTERN HONEYBEE
Worker bees live much shorter lives than queens, even though they are of the same species. Queens are usually killed by their hives when they run out of eggs and become infertile.
Common cow
20 (typically 15–20)
Domestic dog
27 (typically 10–13)
Black garden ant
28
Domestic cat
30 (typically 14)
Giant squid
35
Giraffe
39.5 (typically 20–27)
Common carp
64 (typically 17–20)
Chimpanzee
68 (typically 40–60)
CHIMPANZEE
Humans and chimps share 98.8 percent of their DNA, yet we age slower and live longer than chimps and all our other primate relatives. Precisely why remains a mystery.
Asiatic elephant
79.6
Blue whale
110
Human
122.5 (typically 71*)
*Average worldwide life expectancy at birth in 2021, according to the World Health Organization
Galápagos tortoise
177
GALÁPAGOS TORTOISE
The 177-year official lifespan of this creature is simply the maximum ever measured because records on the tortoise do not date further back. "There may be Galápagos tortoises that are over 200 years old," Magalhães says.
Red sea urchin
200
Rougheye rockfish
205
Bowhead whale
211
Greenland shark
392
Ocean quahog clam
507
Shoestring fungus
2,500
Great Basin bristlecone pine
5,602
Hexactinellid sea sponge
15,000
HEXACTINELLID SEA SPONGE
Most commonly found in deep Antarctic waters, these tube-shaped organisms are fairly simple. Their harsh and cold environment is relatively free of predators and other disruptions, allowing them to live stable, extremely long lives.

Mark Belan; Source: AnAge: The Animal Ageing and Longevity Database/Human Aging Genomic Resources (*longevity data*); Animal Diversity Web (*most of the typical lifespan values*)

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

Mark Belan is a scientific illustrator and visual communicator. His work translates scientific ideas and data into didactic visuals. His work can be found at www.artscistudios.com

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https://www.scientificamerican.com/article/why-some-animals-live-for-only-days-and-others-live-for-thousands-of-years

| Section menu | Main menu |

Animals

- **Whale Songs Follow Basic Human Language Rules**
  Humpback whales learn their haunting melodies in much the same way humans learn words
- **This Butterfly’s Epic Migration Is Written into Its Chemistry**
  Painted ladies travel the globe every year on massive journeys—including across the Sahara
- **Sea Turtle Dance Reveals a Hidden Magnetic Ability**
  Sea turtles are capable of creating GPS-like magnetic maps to guide them back to foraging grounds, and they do a little dance when they recognize those spots

Whale Songs Obey Basic Rules of Human Languages

Humpback whales learn their haunting melodies in much the same way humans learn words

By Cody Cottier edited by Andrea Thompson & Sarah Lewin Frasier

Wordlike sections of humpback whale song follow some linguistic laws of human speech.
John Natoli/Getty Images

For all the world's linguistic diversity, human languages still obey certain universal patterns. These run deeper than grammar and syntax; they're rooted in statistical laws that predict how frequently we use certain words and how long those words tend to be. Think of them as built-in guardrails to keep language easy to learn and use.

Now scientists have found some of the same patterns in whale vocalizations. Two new studies show that humans and whales have converged on similar solutions to the problem of communicating through sound. "It strengthens the view that we should not be thinking about human language as a completely different phenomenon from other communication systems but instead we

should be thinking about what it shares with them," says Inbal Arnon, a psychologist at the Hebrew University of Jerusalem and co-author of one of the studies.

For a paper in *Science*, Arnon and her colleagues analyzed humpback whale songs recorded over eight years in New Caledonia in the South Pacific and found that they closely adhered to a principle called Zipf's law of frequency. This mathematical power law, a hallmark of human language, is observed in our word-use frequencies: the most common word in any language shows up twice as often as the second-most common, three times as often as the third, and so on.

Listen to the humpback whale songs:

But before the researchers could analyze the recordings, they had to identify the segments that were analogous to words (though without semantic meaning) in a stream of otherworldly grunts, shrieks and moans. The scientists found themselves in the same predicament as a newborn baby—so, naturally, that's where they turned for guidance. Human infants "get this continuous acoustic signal," Arnon says, "and they have to figure out where the words are."

A human baby's strategy is simple: listen for unexpected combinations of sounds in adult speech. Whenever you identify one, you've probably located a boundary between words, because those uncommon transitions are less likely to occur *within* words.

When the researchers segmented whale songs based on these "transitional probabilities"—just as a human infant would—Zipf's law of frequency fit the sounds like a glove. And 1,000 arbitrarily shuffled elements of the data came nowhere near a match, strongly suggesting the transitional-probability results weren't a product of random chance. "We were all dumbfounded," says co-author Ellen C. Garland, a whale-song expert at the University of St. Andrews in

Scotland. “There was the possibility of discovering these same structures. Did we think we would? Hell, no.”

Why would the same communicative behaviors evolve independently in whales and humans, whose last common ancestor was a potentially shrewlike creature that lived roughly 100 million years ago? Word distribution according to Zipf’s law of frequency seems to help infants grasp language—and some linguists theorize that such learnability leads to the distribution’s development. “When things are organized that way in your input, you’re going to learn them better,” says study co-author Simon Kirby, a cognitive scientist at the University of Edinburgh.

In other words, the structure of language may be largely a product of how it gets passed from one generation to the next. So the team reasoned that Zipf’s law of frequency might appear not just in human language but also among any other animals whose sequential vocal signals are culturally learned (transmitted between individuals). That group encompasses what Kirby calls “a strange, ragtag bunch of species,” including songbirds, bats, elephants, seals, dolphins and whales. Most other animals that communicate vocally—from dogs to frogs to fish—are thought to use signals that are genetically programmed, not learned.

We now know that whales, at least, share a key ingredient of our own communication system, a finding that fits with the growing attitude among scientists that we aren’t as unique as we once thought. Instead our linguistic capacity rests on a smorgasbord of physical and cognitive traits, many of them spread throughout the animal kingdom.

In a separate paper published in *Science Advances*, Mason Youngblood, a postdoctoral fellow at Stony Brook University, reports evidence of two more language laws in whale vocalizations: One is the brevity law, which, when applied to human language, states that the more common a word is, the shorter it tends to be,

and vice versa. The other is Menzerath's law, which says the longer a linguistic construct (such as a sentence) is, the shorter its constituent parts (such as a sentence's clauses) will be.

Youngblood found that both patterns were especially strong in humpback song but showed up in other whale species, too. These laws describe how animals "maximize the amount of information they convey in the least amount of time and with the least amount of energy," he says.

As tempting as the comparisons with human language may be, the researchers caution against reading too much into these parallels. "Whale song is not a language," Garland says flatly. Although whale calls clearly carry some kind of meaning, she notes that most experts see little resemblance to the depth and complexity of human language. Most important, humpback sounds can't be recombined in endless different ways to express new ideas—an entire song clearly conveys *something*, but the "words" within it seem to lack independent meaning. In that way, whale song is more like music, which also happens to follow Zipf's law.

But the similarities are still striking. Luke Rendell, a biologist at the University of St. Andrews, who was not involved with either study, says these findings could be "telling us something kind of profound about how evolution can either converge at or, perhaps, be constrained to certain types of learning." That is, they might inform us about the range of possibilities for complex communication in any species.

By the same token, Kirby suggests that Zipf's law, and perhaps other linguistic laws, could be "a kind of fingerprint of these culturally evolved systems," present wherever animals have crossed the threshold of cultural learning. "It's probably a very fundamental feature of the organization of cognitive systems," he adds.

Cody Cottier is a freelance journalist based in Fort Collins, Colo.

https://www.scientificamerican.com/article/whale-songs-follow-basic-human-language-rules

This Butterfly’s Epic Migration Is Written into Its Chemistry

Painted ladies travel the globe every year on massive journeys—including across the Sahara

By Jesse Greenspan edited by Sarah Lewin Frasier

Jim Mayes/Getty Images

Painted ladies are the ultramarathoners of the butterfly world—even more so than monarchs. Scientists have long known about their globetrotting tendencies, but only recently have their exact migratory routes come into focus.

Over several generations the butterflies can fly up to 9,300 miles annually from Scandinavia to equatorial Africa and back. Although not every painted lady travels widely, researchers recently detailed in *PNAS Nexus* that certain individuals fly up to 2,500 miles from Europe to overwintering grounds in the African Sahel, journeying over the Mediterranean Sea and the Sahara Desert on the way. A few even inadvertently cross the Atlantic Ocean to South America, other researchers found. In North America, meanwhile, painted

ladies flutter between Mexico and Canada. In Asia, they've even been spotted cutting through the Himalayas.

"They're not passive riders on the wind," says Arthur M. Shapiro, an emeritus lepidopterist at the University of California, Davis. "They're directing themselves." In ideal breeding conditions, "the air is just completely full of them," he adds.

Weighing less than a gram, painted ladies are too light to affix traditional tracking devices to. For the new study, University of Ottawa ecologist Megan S. Reich and her colleagues captured 40 butterflies and discerned their far-off birthplaces based on variants, or isotopes, of the chemical elements hydrogen and strontium in their wings—thereby finding the true long-haulers.

"Sometimes people think of butterflies as really fragile, ephemeral creatures," Reich says. "But they can be quite hardy." Painted ladies are particularly well suited to long-distance travel. No matter the location, innumerable host plants provide them with food. When it gets cold, they shiver to generate body heat. Their triangular forewings propel them at up to 30 miles per hour. Powered by yellow fat reserves, they can fly so high that, until the 2000s, people in the U.K. virtually never observed them leaving the country and therefore thought they might be dying off each winter.

Yet painted ladies are not unique. Hundreds, if not thousands, of insect species most likely migrate, including dragonflies that cross the Indian Ocean, moths that traverse Australia and plant hoppers that windsurf through East Asia. "There are some incredible insect migrations," Reich says, most of which are never recorded.

Jesse Greenspan is a San Francisco Bay Area–based freelance journalist who writes about history and the environment.

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https://www.scientificamerican.com/article/this-butterflys-epic-migration-is-written-into-its-chemistry

The Surprising Importance of This Adorable Sea Turtle Dance

Sea turtles are capable of creating GPS-like magnetic maps to guide them back to foraging grounds, and they do a little dance when they recognize those spots

By Jack Tamisiea edited by Andrea Thompson & Sarah Lewin Frasier

Loggerhead turtle hatchling.
foryouinf/Getty Images

To juvenile loggerhead sea turtles, a tasty squid might as well be a disco ball. When they sense food—or even think some might be nearby—these reptiles break into an excited dance. They tilt their head toward the surface, open their mouth and flap their front flippers in a swim stroke that resembles a doggy paddle. Sometimes they twirl in place like a top.

Researchers recently used this distinctive behavior to test whether loggerheads could identify the specific magnetic field signatures of places where they had eaten in the past. The results, published in *Nature*, reveal that these rambunctious reptiles dance when they encounter magnetic conditions they associate with food.

According to the study's lead author, Texas A&M University marine biologist Kayla M. Goforth, the findings show that loggerhead sea turtles can learn locations' magnetic signatures. This information helps them create a magnetic map akin to a GPS, she says.

Loggerheads and other sea turtles are renowned for their far-ranging migrations, in which they travel thousands of miles without losing track of where they started. Many sea turtles come back to specific foraging grounds year after year, and females often return to lay their own eggs at the same beaches where they hatched.

Scientists have known for decades that sea turtles use Earth's magnetic field to orient themselves as if they have a built-in magnetic compass. But accurately navigating back to a specific location requires knowing not just the direction in which they are traveling but also the precise coordinates they are heading to. Some scientists have theorized that sea turtles can learn specific magnetic coordinates of foraging grounds and nesting beaches, perhaps sensing factors such as magnetic field intensity.

To put that idea to the test, Goforth and her colleagues collected several loggerhead hatchlings on an island off North Carolina. (The turtles were returned to the wild the following summer.) In the laboratory, the turtles were placed in buckets that were hooked up to a magnetic coil system; running an electric current through the system created a magnetic field in the bucket. The scientists calibrated these fields to replicate the magnetic conditions of various locales along the Eastern Seaboard, such as spots in the Gulf of Mexico or along the coast of Maine.

A loggerhead sea turtle "dancing" in response to the magnetic signature of a spot it associates with food.
Goforth et al., *Nature* (2025)

Each juvenile loggerhead was exposed to two distinct magnetic fields. Over a two-month conditioning period, the turtles spent equal amounts of time in each field—but got food in only one of them. Then, during experimental trials over several consecutive days, the team re-created the two magnetic fields but did not feed the turtles.

The scientists discovered that, even with no food present, the sea turtles displayed their dancing behavior when they encountered the magnetic conditions associated with past feedings. This reaction supports the notion that these animals can learn foraging locations' magnetic coordinates. A similar ability has been observed in salmon as they venture to and from oceanic feeding grounds. (As to why the turtles dance, Goforth says they just "get really excited in any situation when you're giving them food like that.")

The researchers tested the loggerheads again after several months without reexposing them to the two magnetic fields to determine whether the turtles retained these coordinates over a longer period. The animals still danced when they encountered the magnetic conditions associated with food.

According to Goforth, these turtles can probably remember magnetic coordinates for several years or even decades. “In the wild, they retain feeding information from when they are hatchlings to adults, which is a 20-year time span,” she says.

Marine biologist Jeanette Wyneken, who studies sea turtles at Florida Atlantic University and was not involved in the new research, says the ability to learn geomagnetic coordinates emphasizes how crucial food sources are for growing sea turtles. “It’s very important for young sea turtles to outgrow [the size of] predator mouths as quickly as possible,” she says. The turtles “need to efficiently locate food to sustain their development and increase their chances of survival.”

Goforth and her colleagues also wanted to determine whether the sea turtles’ magnetic mapping capabilities were linked to their internal magnetic compass. The researchers ran similar experiments but added radio-frequency waves, which disrupted the animals’ ability to orient themselves via magnetic fields. They discovered that the turtles could still recognize specific magnetic coordinates.

The findings suggest sea turtles possess two distinct senses for detecting magnetic fields—one for sensing direction and one for other magnetic features. Past work has indicated some songbirds and newts also possess dual magnetoreception systems. Because birds and amphibians are only distantly related to sea turtles, Goforth and her colleagues think magnetic compasses and maps might be a common feature in the vertebrate travel toolbox.

Jack Tamisiea is a science journalist based in Washington, D.C., who covers natural history and the environment. Follow Tamisiea on Twitter @jack_tamisiea

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https://www.scientificamerican.com/article/sea-turtle-dance-reveals-a-hidden-magnetic-ability

Arts

- **Poem: ‘Live and in Color’**
  Science in meter and verse

Poem: ‘Live and in Color’

Science in meter and verse

By E. M. Teichman edited by Dava Sobel & Clara Moskowitz

Masha Foya

In the blink of an eye
the land bloomed with a spectrum of brilliant color
where before it was all greens
and earth tones.

It was the sudden awakening of a new aesthetic;
our “shrew-like” ancestors, and every creature,
quickly learned to see and enjoy
a palette never before seen.

It was a worldwide revolution of technique and delight
which robustly punctuated
the equilibrium
of evolution.

The knowledge of how to manufacture bold color
gave flowering plants a commanding advantage
over other plants.
They could now visually signal the animal kingdom
in a simple and powerful way,
and thereby commandeer legs and wings to carry their pollen.
Flowering species quickly dominated the plant kingdom.
Today 90 percent of plant species are angiosperms.

We associate flowers with nature itself;
but flowering plants are a johnny-come-lately;
they are a recent idea.
For 97 percent of Earth's existence there were no flowers.
For 96 percent of life's existence there were no flowers.
For 89 percent of the existence of plants there were no flowers.
A recent idea.

Animals select their mates based on what they find beautiful,
and so we have all created ourselves in our own image of beauty.
Immediately following the aesthetic revolution brought by the bold colors of flowers,
small, tree-dwelling dinosaurs,
not too concerned about staying camouflaged,
looked at these colors
and flew with them.

E. M. Teichman is an architect practicing in Sea Bright, N.J. On Sundays, when the firearms are silent, he wanders the hills of eastern Pennsylvania looking for poems.

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https://www.scientificamerican.com/article/poem-live-and-in-color

Astronomy

- ## How Can We Know If an Asteroid Will Hit Earth?

  “Keep your eye on the ball” is a motto for many athletes—and for astronomers trying to find Earth-threatening space rocks

How Can We Know If an Asteroid Will Hit Earth?

“Keep your eye on the ball” is a motto for many athletes—and for astronomers trying to find Earth-threatening space rocks

By Phil Plait edited by Lee Billings & Clara Moskowitz

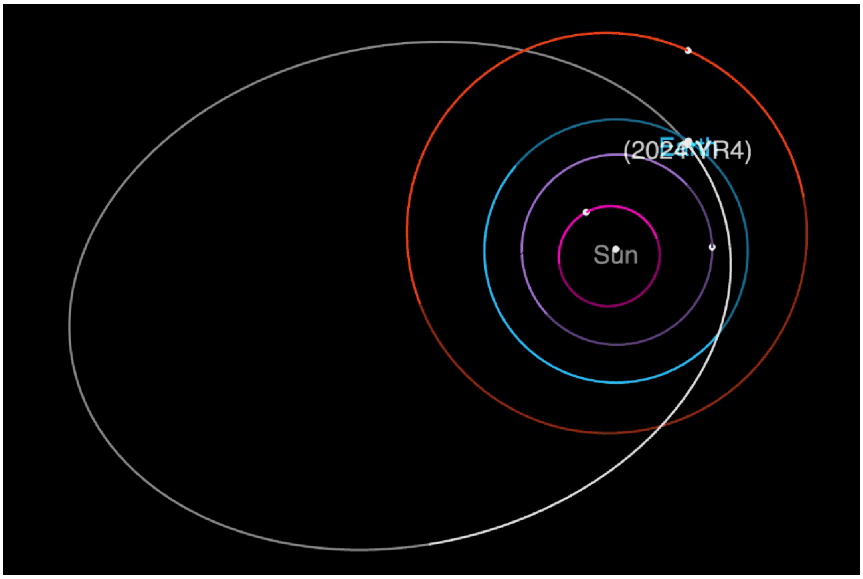
Meteor Crater in Winslow, Ariz.
Larry Gerbrandt/Getty Images

You’ve no doubt seen this kind of news headline: “Astronomers Say Space Rock May Hit Earth in the Not-Too-Distant Future!” We usually get such warnings about one or two objects every year; the latest iteration concerns an asteroid, 2024 YR4, that is estimated to be more than 50 meters wide. For a while there was a several percent chance of its impacting Earth, but after more observations, by the end of February 2025 an impact had essentially been ruled out.

But how can anyone know such things? How do astronomers find these asteroids and then determine where they’ll be many years into the future?

We've actually known how to do this for centuries thanks to German astronomer Johannes Kepler, who first figured out the requisite orbital laws in the 17th century. Since that time, the advent of better telescopes, digital cameras and fast computers has made the task much easier—though by no means foolproof.

There are around a dozen currently operating survey-type telescopic observatories that take wide-angle images of the sky every night and look for undiscovered objects zipping through our solar system. Seen from Earth, such objects appear to move relative to the far more distant "fixed" stars. Astronomers used to look for such motions by eye with photographs, but automation can now perform this task far faster and more accurately.



The predicted orbit of the asteroid 2024 YR4 as animated in 3-month intervals per frame, beginning on December 22, 2024 and ending on December 22, 2032.
NASA/JPL-Caltech

Once a new moving object is found, its orbit needs to be determined. Is it on a circular path out past Mars, or does it have an elliptical orbit that brings it close to Earth? This is where Kepler and his laws come in.

He figured out that all orbits have one of three shapes: elliptical, parabolic or hyperbolic. (A circle is just an ellipse where the long and short axes are equal, so we lump circles in with ellipses.)

Parabolic and hyperbolic orbits are what we call “open,” meaning they don’t close back on themselves. An object on an orbit like that is just passing through; it’s moving rapidly enough to escape the sun’s gravity and disappear into interstellar space. Most comets that fall in toward the sun from beyond Neptune have nearly parabolic orbits. Only two objects have ever been found on extremely hyperbolic orbits: ‘Oumuamua and the comet 2I/Borisov.

But an object on an elliptical orbit is bound to the sun and should orbit it indefinitely (unless it gets a gravitational kick from a planet, say). Our ability to predict a sun-orbiting object’s future position comes from understanding everything we can about its ellipse.

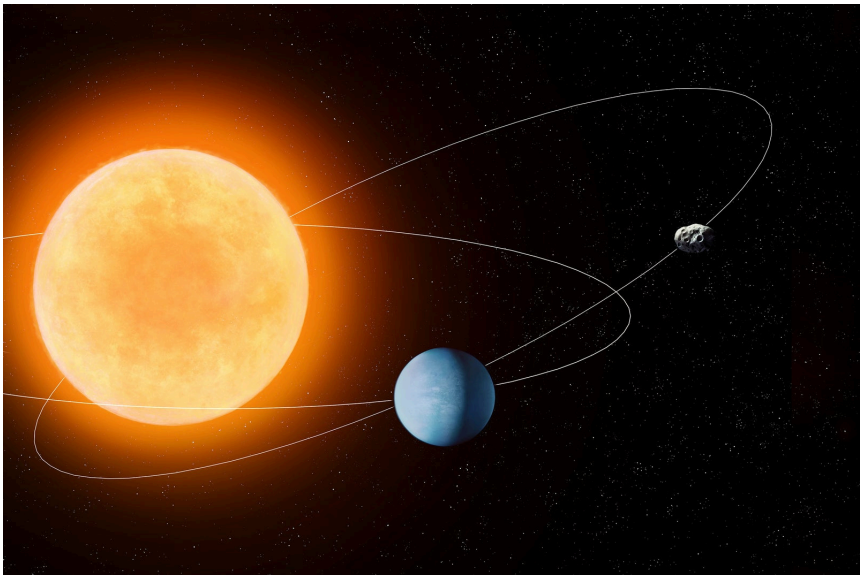
> We must keep our eyes on the sky. The good news is that even more telescopes are coming online, including the huge Vera C. Rubin Observatory in Chile and NASA’s NEO Surveyor.

The basic characteristics of an orbital ellipse are its size (mathematically, half the length of its long axis, a measurement called the semimajor axis), its eccentricity (which essentially measures how elliptical it is: 0 is circular, and 1 is infinitely stretched out, like a line), and its orientation in space. An object’s orbital ellipse can be tipped relative to that of Earth, for example, with its long axis pointed in some particular direction in space. Once we know all those parameters (called the orbital elements), we can mathematically define the associated ellipse. If we also know an asteroid’s position along its ellipse, say, on the date it was discovered or at a specific time during a subsequent observation, Kepler’s equations tell us where along its orbit the asteroid should be on any given day—well, in theory.

In practice, it’s not so easy. Forecasters usually need at least three well-separated observations of an asteroid to start nailing down all the variables governing the ellipse’s shape. And those observations are not exact: asteroids don’t look like perfect tiny dots in an image

but instead are smeared out a bit, making it hard to know their precise position as they shift against the background stars.

Such imprecisions may be small, but they add up. Thus, the result usually isn't an ideal ellipse, and the calculated path of the asteroid is fuzzy; in reality, its position might be a bit off from the predicted location. The further into the future (or past, for that matter) you try to calculate the position, the worse the prediction gets. It's like the actual path of the asteroid is a cone with its vertex at the present position, opening up toward the direction in which you're trying to make predictions. Statistically speaking, the rock could be anywhere inside that cone, and that can add up to a large volume of space.



A not-to-scale illustration of an asteroid's orbital path crossing the orbit of Earth around the sun.
Nazarii Neshcherenskyi/Getty Images

The only way to narrow that path down is to get more observations, either fresh from telescopes or retroactively found in archival data. Also, the longer an object is observed, the more certain its orbital-element measurements become.

It's like being an outfielder in a baseball game. Imagine the pitcher throws the ball, but one second after the batter hits it, you have to close your eyes and guess where it will be so you can catch it. You can make a decent estimation, but it won't be anywhere near

accurate enough to guide you. You must be able to keep your eye on the ball and watch as it moves to maximize your chances of making the catch.

So we aim to observe asteroids for as long as possible to increase the temporal baseline of observations. There are obstacles, though: some asteroids are small and decrease in brightness rapidly as the distance between them and Earth increases. This is the case for 2024 YR4, which is now moving away from Earth and forecasted to fade from view in late April. Asteroids can also avoid observation by getting so close to the sun in the sky that they can't be seen for several months.

Assuming, however, that an asteroid's orbit is well constrained and predictable, how do we know what the odds are of an Earth impact? There are many methods for calculating this likelihood; one way is to simulate the orbit and note the dates when the object is in Earth's orbital vicinity, then determine whether our planet will be in its path at the same time. If so, well, that's bad.

But not necessarily catastrophic. Earth is a small target, and the statistical volume of space the asteroid can be in on that date is usually large. Even for an apparently alarming asteroid, there's only a chance we'll get hit, and it's usually very low, especially the further in advance we try to predict it. Typically the odds of impact for any newfound potentially Earth-threatening space rock are one in thousands.

In most cases, better observations nail down the path and show that it passes well away from Earth, and the odds drop effectively to zero. Irritatingly, the statistical chance of impact sometimes increases first—which is what happened with 2024 YR4. Remember, the asteroid is somewhere near the vertex of a large cone, and we don't know where. If Earth is near the cone's centerline, then as the cone narrows with better observations, we're still inside it. The chance of impact goes up. But then, almost

always, the cone narrows further and winds up pointing in a slightly different direction, leaving Earth safely outside it, and we can all breathe a sigh of relief.

That's not to say we never get hit! Examples abound, such as the Chelyabinsk asteroid that exploded over Russia in 2013, the Tunguska event in Siberia in 1908 and the impact that formed Arizona's Meteor Crater 50,000 years ago. Every day Earth plows through roughly 100 tons of interplanetary material, the vast majority of which is composed of tiny rocks that wind up as lovely meteors streaking across our sky. But sometimes those chunks of debris are bigger—much bigger. The bigger they get, the rarer they become, so truly devastating impacts are few and far between.

They do happen, though, so we must keep our eyes on the sky. The good news is that even more telescopes are coming online, including the huge Vera C. Rubin Observatory in Chile and NASA's NEO Surveyor (planned for launch in 2027), and they should help us not just map where these objects are and where they're headed but also determine their size and what they're made of. If some asteroid big enough to do damage has us in its crosshairs, we hope we'll know about it as soon as we can, giving us enough time, perhaps, to do something about it.

The more telescopes we have covering the greatest amount of sky over time, the better.

Phil Plait is a professional astronomer and science communicator in Virginia. His column for *Scientific American*, The Universe, covers all things space. He writes the *Bad Astronomy Newsletter*. Follow him online.

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Behavior

- **Dolphins Communicate with ‘Fountains of Pee’**
  This discovery adds to a growing list of how animals talk with their urine
- **Why You Shouldn’t Ignore Loud Snoring in Kids**
  Snoring indicates oxygen reduction, but a variety of treatments can restore healthy airflow

Dolphins Communicate with ‘Fountains of Pee’

This discovery adds to a growing list of how animals talk with their urine

By Gennaro Tomma edited by Sarah Lewin Frasier

EriCatarina/Getty Images

Humans typically consider peeing a private act. But for many animals, it’s a crucial way to share information—one that goes way beyond simply marking territory. Scientists are increasingly aware of urine communication in all its startling forms.

“Animals in general want to learn as much as they can about other animals, such as their sex, dominance, species, and so on,” says Thomas Breithaupt, a sensory ecologist at the University of Hull in England, “and a lot of information is in the urine.”

Recently researchers documented Amazon River dolphins (*Inia geoffrensis*) performing a curious behavior: aerial urination. A male turns on its back at the water’s surface and ejects a stream of pee into the air—and almost 70 percent of the time, the team reported

in *Behavioural Processes*, a nearby male “receiver” approaches this spontaneous fountain.

The researchers speculate that male dolphins might use aerial peeing to deliberately communicate their “social position or physical condition,” says study co-author Claryana Araújo-Wang, a biologist at Botos do Cerrado Research Project in Brazil. Further experiments are needed to pin down precisely what’s happening, says Joachim Frommen, a behavioral ecologist at Manchester Metropolitan University in England, who was not involved in the study.

But this is just the latest in a long and varied list of the stories that urine can tell. In primates, it can provide clues about an individual’s species, gender and group membership “and could support both individual recognition and the finding of mating partners,” says Marlen Kücklich, a behavioral ecologist at Leipzig University in Germany. Some primates even wash themselves with their own pee. This behavior is not fully understood, but the authors of a study on capuchin monkeys proposed that males might attract females via urine’s testosterone content.

In aquatic environments, some fish use urine to communicate their size and aggressiveness before fights. For a few crustaceans, such as lobsters—which pee from their heads—urine can also convey information about social status and readiness to mate. Female stickleback fish get information on a male’s immune system by sniffing its urine, and they tend to choose males with “immune systems that are very comparable to or compatible with their own,” Frommen says.

“When it comes to communication, humans always focus on visual cues and acoustic cues because we are visual animals and acoustic animals,” Frommen adds. But smell is a crucial sense, too, though understudied in some species, and urine is a major provider of olfactory information. In recent years, he says, “people became

more aware that we are focusing on a very limited area of communication, and more and more studies started thinking about smell.”

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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| Section menu | Main menu |

Why You Shouldn’t Ignore Loud Snoring in Kids

Snoring indicates oxygen reduction, but a variety of treatments can restore healthy airflow

By Lydia Denworth edited by Josh Fischman

Jay Bendt

The rattling or whistling noises of regular snorers are famously hard on those who share their beds. Middle-aged men and people who are overweight come frequently to mind as perpetrators because they are the most common sufferers of sleep apnea, often caused by a temporarily collapsing airway that makes the person snore heavily. But recent studies in children and pregnant women have revealed that even mild snoring can negatively affect health, behavior and quality of life.

“We know that disordered breathing and disturbed sleep can have myriad physiological effects,” says Susan Redline, a pulmonologist and epidemiologist at Brigham and Women’s Hospital in Boston.

“More people have sleep-disordered breathing than have overt apneas. We shouldn’t forget about them.”

Almost everyone snores occasionally. Allergies and respiratory infections can trigger it. When the upper airway at the back of the throat narrows, it causes the tissues there to vibrate, creating the familiar rumble. Physicians worry if people habitually snore three or more nights a week, especially if they have other red flags such as unexplained high blood pressure.

The category of sleep-disordered breathing includes apnea’s total pause in breathing, shallow breaths called hypopnea, snoring without apneas, and a subtler problem called flow limitation in which the shape of the airway is narrowed but the sleeper makes no noise. The standard measure of severity is the apnea-hypopnea index (AHI), which counts pauses in breathing per hour and associated drops in oxygen levels. The normal level in adults is fewer than five pauses; more than 30 is severe. In children, 10 pauses could be considered moderately severe.

> It’s wise to pay attention not just to snoring but to other aspects of sleep such as duration and variability.

But in kids, it turns out the AHI isn’t always the best indicator of potential negative effects. A 2023 clinical trial published in the *Journal of the American Medical Association* followed 458 children aged three to 12 years with mild sleep-disordered breathing—an AHI of zero to three. Half got early treatment with tonsil surgery, long the most common approach for children who snore because tonsils can grow faster than young airways and cause obstructions. The other half were followed with “watchful waiting.” After 12 months no cognitive differences emerged between the two groups, but those who had surgery saw improvements in problem behaviors such as inattention and in socializing and emotional regulation. Their parents also reported less sleepiness, improved quality of life, and other benefits. And

blood pressure, though not in the hypertensive range for anyone in the study, dropped in those who had surgery and went up in those who did not. (Adults who snore are at greater risk for hypertension.)

“The beauty of the trial is that it recruited children who wouldn’t necessarily be treated” because of their mild conditions, says pediatric pulmonologist Ignacio Tapia of the University of Miami Miller School of Medicine. Yet such children “would benefit from early treatment. It opens up a whole new avenue.”

In two recent papers using data from nearly 12,000 children enrolled in the ongoing Adolescent Brain Cognitive Development study, pediatric otorhinolaryngologist Amal Isaiah of the University of Maryland School of Medicine and his colleagues also found that habitual snoring (reported in about 700 of the children) was associated with behavioral issues such as an inability to follow rules or form friendships.

Isaiah found no cognitive problems among kids who snored, but his team did identify cell losses in the prefrontal cortex. That’s a part of the brain that is involved in behavioral control. “The prefrontal cortex is susceptible to hypoxia,” Isaiah says. “This area is undergoing protracted development throughout childhood. If you additionally expose it to stresses such as snoring, the brain’s compensation may not be sufficient in some children.”

In terms of pregnancy, in a 2022 study, nearly 2,000 women underwent a sleep study while they were pregnant. More than half were assessed two and seven years later. For participants with an AHI score above five, risk increased more than threefold for hypertension and twofold for a cluster of problems called metabolic syndrome. And in a 2024 study, pregnant women with flow limitation were at increased risk of preeclampsia and other complications.

Redline suspects that sleep-disordered breathing, even without apnea, increases the body's workload and overstimulates the part of the nervous system that helps to control organs such as the heart and lungs.

Because of this issue, sleep psychologist Ariel Williamson of the University of Oregon points out that it's wise to pay attention not just to snoring but to other aspects of sleep such as duration and variability, which have also been linked to emotional and behavioral functioning in children and to cognitive problems in adults. "Snoring could be the cause of the concern you're seeing," she says, but if not, "then there may be other sleep issues going on."

Fortunately, there are treatments for children and adults. In children, as the clinical trials indicate, removing tonsils can benefit even those with mild snoring. For adults and a few children, continuous positive airway pressure (CPAP) masks, which keep airways open, are still the first option for apnea and can help habitual snorers as well. Some people find wearing CPAP masks intolerable, though. For them, a surgical solution called hypoglossal nerve stimulation, using an implanted device, can also work. Oral appliances such as the mandibular advancement device, a custom-fit mouth guard that holds the airway open without surgery or CPAP, is another option. Still other patients have success with "positional therapy" devices that help to keep them on their side during sleep, where they are less likely to snore.

At every age, losing weight and increasing physical activity improve sleep quality. And adhering to an anti-inflammatory diet—such as one that includes more omega-3 fatty acids—can help reduce snoring.

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

https://www.scientificamerican.com/article/why-you-shouldnt-ignore-loud-snoring-in-kids

Climate Change

- **There Is No Such Thing as a Climate Haven**
  Climate change is everywhere. Moving to a new place because it seems less affected is a fool’s errand

There Is No Such Thing as a Climate Haven

Climate change is everywhere. Moving to a new place because it seems less affected is a fool's errand

By The Editors

Martin Gee

In September 2024 Hurricane Helene flooded the mountain town of Asheville, N.C., which had once been called a climate haven, a place less prone to the toll of climate change. In March 2025 fires coursed throughout the state. Fires also claimed Myrtle Beach, on the South Carolina coast. From sea to sky, the Carolinas have been grappling with disaster.

All the while, people make lists of places in the U.S. that are supposedly more resistant to climate change. They lie farther north,

presumed to be better insulated from global warming, or near rivers or lakes that would ballast drought. Buffalo, N.Y., Ann Arbor, Mich., Burlington, Vt. Not to mention Asheville.

But what befell Asheville illustrates how no place in the U.S.—in the world, really—is safe from the ravages of the climate crisis. There are no climate havens. Places touted as less prone to heat, such as Asheville, are subject to floods and more intense snowfall. Those close to water face rising sea levels or floods. Population growth would strain water supplies, eventually spoiling these places as the rest of the country continues to endure more intense wildfires, more destructive hurricanes and tornadoes, prolonged droughts, and intensifying heat waves. There is nowhere to run to get away from climate change.

Earth's temperature is increasing, polar ice is melting, and the northern U.S. is seeing summer heat like never before. Winter freezes are crippling the power grid in Texas and other southern regions. Migration is not a quick fix for the climate crisis, and it certainly isn't the most equitable. We must recognize that in addition to curbing our fossil-fuel use, adequately fortifying and restructuring the spaces we already have will give us and the next generations the best possible chance of survival.

> How every level of government chooses to respond to this crisis will matter.

First and foremost, we need governance at all levels to accept not only that climate change is real but that it is something we must both adapt to and mitigate. These two ideas are not mutually exclusive—choosing adaptation, or changing our local environments to make them more resilient to climate change, doesn't mean we no longer try to slow that change.

Perhaps on top of its favorable location and weather, Asheville was considered a climate haven because its local government has

accepted the reality of climate change. Before the floods came, the city had approved its Municipal Climate Action Plan, setting goals for renewable energy, more sustainable infrastructure and reduced waste production in the city. The plan states that one of its goals is an increase in renewable energy generation, including the use of solar panels to power city-owned properties and adherence to sustainable practices for new construction and retrofits. But with the loss of tree cover and the demands of a growing population making Asheville more vulnerable to landslides, the city will have to continue to adjust—as will the state, which has its own climate resiliency plan.

But will North Carolina be able to use disaster relief to push through a sustainable recovery under threat from the politicization of climate change? The state's resiliency office is underfunded even though the new governor, Josh Stein, campaigned in part on building a state better able to withstand the effects of climate change. It's not immediately clear how his slew of disaster-related executive orders about temporary housing and rebuilding roads and bridges will factor into adaptation efforts.

What is clear is that the idea that people will be able to up and move to some cities or states that seem more able to withstand our climate crisis is profoundly unjust. The median home price in Washtenaw County, Michigan, where Ann Arbor is located, is about $380,000. That makes it the second-most expensive county in the state. Other Michigan counties are significantly cheaper, but few are prepared, or even preparing, for permanent population increases. Winter is getting shorter along the Great Lakes, and not only is flooding becoming more of an issue, but the weather is getting hotter. Even housing prices in Buffalo are increasing.

The bottom line is that historically mild weather, historically agreeable climates and historically responsive governments have made some places in the U.S. seemingly more resistant to the effects of climate change. But the crisis knows no boundaries—

Canadian wildfires blew smoke into New York City last summer and blanketed Buffalo the year before. Even adaptation won't completely solve the problem.

In the end, how every level of government chooses to respond to this crisis will matter. Individual cities can't manage this problem alone, and neither can states. How will cities such as Austin, Tex., make meaningful adaptations in one of the U.S. states most susceptible to global warming if its governor and legislature largely downplay climate concerns and actively thwart efforts to reduce fossil-fuel use? Texas's water supply is in dire straits, and far too many people there and in places such as Arizona will be left behind in this great migration north.

And how will we fare as a nation under an administration that denies climate change is real? One that is actively rolling back environmental protections, throwing out environmental justice cases, and promoting the production of more and more fossil fuels?

The idea that any one place in any nation is more resistant or more resilient to forces that are global in nature is clever marketing and nothing else. The message might make people feel better by letting them believe they can just escape the climate crisis by moving to a different city, but this is a bill of goods. Our entire planet is in the throes of warming. Rather than trying to outrun it, we must demand leadership that will help fund our efforts to adapt, look to state and local leaders to make those adaptation plans reality, and continue to seek ways to change the very things that started this climate-haven conversation in the first place—burning fossil fuels and abusing our forests, farmlands and good fortune.

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https://www.scientificamerican.com/article/there-is-no-such-thing-as-a-climate-haven

Culture

- **Beautiful Shapes, a Magic Molecule and Elephant Bromances**
  The May issue of Scientific American takes you on a deep-sea mining mission, explores dark comets and examines an invisible threat to the food we eat
- **Contributors to Scientific American’s May 2025 Issue**
  Writers, artists, photographers and researchers share the stories behind the stories
- **Readers Respond to the January 2025 Issue**
  Letters to the editors for the January 2025 issue of Scientific American

Beautiful Shapes, a Magic Molecule and Elephant Bromances

The May issue of Scientific American takes you on a deep-sea mining mission, explores dark comets and examines an invisible threat to the food we eat

By Jeanna Bryner

Scientific American, May 2025

Ask someone to name a favorite shape, and they'll probably choose one of the usual suspects: triangle, circle, maybe a trapezoid. These run-of-the-mill forms take a back seat to more sophisticated and mind-bending structures in our cover story, in which writer Rachel Crowell asks mathematicians to describe their most adored shape. The responses are not only colorful; they also illustrate why mathematics once fell under the rubric of natural philosophy. The drive to understand the natural world, often through abstract thinking, becomes clear in some of the essays. For instance, one mathematician says, "My favorite shape is the loop, a circle with all geometric information stripped away, leaving only a free-form

one-dimensional object.” Other geometric gems include a hyperbolic pair of pants, a hollow form with a waist and two ankles, and a permutahedron, “the site of a beautiful, productive dialogue among geometry, algebra and combinatorics.”

Journalist Willem Marx writes a riveting feature about the behemoth machines plunging their metallic claws into the South Pacific seafloor off Papua New Guinea (PNG) to mine metals and minerals that are critical to the economy. We the readers enter the story as Marx boards a privately owned ship, telling us he’s not sure why the operators allowed a reporter to observe such a brazen project. Marx follows a slew of leads on land and at sea to find out how aware PNG regulators were of this operation, as well as to uncover the identities of the overseas billionaires funding it, reactions from locals and the effects of the mining on deep-sea habitats. The insights he gains about this venture suggest “a new era of deep-sea mining had all but begun.”

A cosmic mystery unfolds, as science writer Robin George Andrews plays detective on the case of some misbehaving space objects now called dark comets. I’ve long been fascinated by investigations into our solar system’s first known interloper, a cigar-shaped structure called ‘Oumuamua whose origins remain elusive. Now, however, astronomers have found a group of dark comets that share some of the interstellar visitor’s oddities: they accelerate around the sun with no apparent means. These cometlike objects fall into two families, the “innies” and the “outies,” Andrews says. One suggested explanation that may resonate with *Severance* fans: the innies that inhabit the inner solar system are remnants of their former selves, the outies.

Scientists had long thought male African elephants were relatively solitary creatures with simple social lives compared with those of the females in this matriarchal species. That idea is being turned on its head as research reveals the males are sensitive animals that crave bromances. Behavioral ecologist Caitlin O’Connell tells us

these bachelors aren’t loners—instead they form tight-knit social networks in which males support one another and even fight off would-be bullies.

Elephants are the largest land mammals, but a teensy parasite is wreaking outsize havoc in the natural world. This mite, called tropilaelaps, is killing off honeybee populations in Asia and Europe, leaving the agricultural crops they pollinate in dire straits, writes journalist Hannah Nordhaus. If beekeepers and scientists can’t get a handle on the itty-bitty foe in time to keep it out of the Americas, the result could be scarce and expensive produce, beef and dairy because honeybees pollinate cattle feed as well as fruits and vegetables.

The COVID pandemic brought some microscopic bugs into clear view. Now, with bird flu on the rise and norovirus having a heyday, senior features editor Jen Schwartz asks whether the nontoxic disinfectant hypochlorous acid could keep these killers at bay. The weak acid is 100 times more effective than bleach at lower concentrations. When used as an eye cleaner, it can vanquish bacteria, and it has been studied as a nasal rinse to treat infections. It can also disinfect indoor surfaces as a fog or spray. Because the chemical is unstable, it has been slow to hit the market at a large scale. That’s now changing as companies bring it to shelves—sometimes as a beauty product loaded with extra ingredients. Stay safe and informed, everyone.

Jeanna Bryner is managing 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/beautiful-shapes-a-magic-molecule-and-elephant-bromances

Contributors to *Scientific American*'s May 2025 Issue

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

By Allison Parshall edited by Jen Schwartz

Caitlin O'Connell.
Max Salomon

Caitlin O'Connell

Secrets of the Pachyderm Boys Club

Caitlin O'Connell (*above*) still gets emotional when she remembers her first encounter with an elephant. When a bull stepped in front of her vehicle in South Africa's Kruger National Park, she looked up into the face of what felt like an old man. "This person has lived for so long, and what is his experience?" she thought. As a scientist

studying elephant communication, she sees many parallels between these animals and humans. For example, “some young bulls will follow an older buddy and feed them” when they’re too old to eat on their own, she says. “This is part of what I want to get across: it’s so important for the young bulls to have these mentors,” she says of her article in this issue. “It makes an inordinate difference to their whole population.”

O’Connell first studied plant hopper insects, which communicate through sound waves that travel through plant stems or leaves. Then, while working at a national park in Namibia during a gap year after her master’s program, she noticed elephants might be doing something similar. It took a decade to prove that elephants communicate with seismic rumbles, and now more sophisticated tools are allowing scientists to start decoding their meaning. Researchers have revealed that elephants are using something akin to vowels and even calling one another by name. “We’re really at the forefront of some breakthroughs here.”

Mark Belan
Graphic Science

Mark Belan wants to make science sexy. “It’s kind of tongue-in-cheek,” he says, but this goal nonetheless guides his work as a scientific illustrator. Science, he thinks, has acquired a reputation for being dense and dull, but to him it’s “the greatest story ever told.” As a graphics journalist, Belan aims to translate that wonder into eye-catching visuals that inspire people to appreciate sea slugs and ant colonies and other overlooked natural phenomena.

For this issue’s Graphic Science, written by *Scientific American* senior editor Clara Moskowitz, Belan charted the lifespans of some of Earth’s most incredible creatures, from fleeting worms to 15,000-year-old sea sponges. His graphic, which has a playful, toylike quality, invites readers into a 3D space alongside the data.

“Looking at the diversity of lifespans across species on our planet really tickles the brain,” encouraging people to wonder how it all evolved, Belan says. This project reminded him of his master’s degree studies in geochemistry and astrobiology; he examined the biological footprints life leaves behind to potentially seek them elsewhere in the universe. “Chemistry and physics exist beyond Earth, right? Biology must, too,” he says. “So if we have this huge diversity just on Earth, I think it opens a question of what else is out there.”

Willem Marx
Deep-Sea Mining Begins

For London-based journalist Willem Marx, the circumstances around his feature on deep-sea mining were doubly unusual. First, “it rarely happens that the industry at the center of controversy says [to a journalist], ‘Come and have a look,’” he says. Yet that’s precisely what happened: Marx visited the MV *Coco* off the coast of Papua New Guinea to observe some of the first commercial deep-sea mining operations. Second, when Marx asked residents for their perspectives on the mining, it turned out they were learning about it for the first time—which made Marx’s role part of the story. This was “a bit unnerving” for a journalist accustomed to being a mere observer, he says.

Marx travels often for assignments—when we spoke over the phone for this interview, he was reporting in Rome on the pope’s health. His time onboard the *Coco* was far from his first work trip at sea; in fact, he’d visited the very same ship while writing about the recovery mission for the *Titan* submersible, which imploded on its way to visit the *Titanic* wreckage.

This stint on the *Coco* came with an unusual requirement: a three-day safety course that involved plunging upside down into a pool in a mock helicopter, then breaking the helicopter window to swim

out. “That’s a pretty intense requirement for a story outside of a combat zone, as far as I’m concerned.”

Hannah Nordhaus
A New Threat to Honeybees

In 2006 worker bees in hives across the U.S. began disappearing. The causes of this devastating phenomenon, called colony collapse disorder, remain largely a mystery, says journalist Hannah Nordhaus, who covered this event in her 2011 book, *The Beekeeper’s Lament* (Harper Perennial). But the epidemic probably had something to do with varroa mites—tiny parasites the industry had been battling for years. As Nordhaus writes in her feature for this issue, there will soon be a new, more deadly mite in town. Tropilaelaps, or tropi, mites “add another element of precarity” to the already risky beekeeping industry on which so many crops depend, she explains. Like this story, “all my bee stories have started with people,” Nordhaus says. This article begins with Sammy Ramsey of the University of Colorado Boulder, who is sounding the alarm on tropi mites.

Nordhaus, who lives in Boulder, was raised in Washington, D.C., in a family involved in politics and environmentalism. Her roots, though, are farther west. Her second book, *American Ghost* (HarperCollins, 2015), tells the story of her great-great-grandmother, whose ghost was said to haunt a hotel in Santa Fe, N.M. As soon as Nordhaus had the opportunity, she moved out west, where her passions for history and the environment are both engaged. “In any history of the American West, there’s always an environmental strand that weaves through it.”

Allison Parshall is an associate editor at *Scientific American* covering mind and brain. She writes the magazine's Contributors column and 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. Follow Parshall on X (formerly Twitter) @parshallison

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Readers Respond to the January 2025 Issue

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

By Aaron Shattuck

Scientific American, January 2025

HIDDEN PLANET

After I read "The Hunt for Planet Nine," by Robin George Andrews, it occurred to me that one thing that should be discussed is the possibility of sending a probe out to this hidden planet in our solar system, should the new Vera C. Rubin Observatory confirm its existence.

JAMES W. SCOTT *VERNON, N.J.*

If new instruments and surveys provide clear evidence that Planet Nine likely exists, but then it continues to evade detection, that

would increase speculation that it might be a primordial black hole. Would there be any hope of detecting such a black hole?

RON PHILO *KANSAS CITY, KANS.*

What are the chances that Planet Nine is a brown dwarf? That could explain its elusiveness.

CAROLINE KIRSCH *VIA E-MAIL*

ANDREWS REPLIES: *To answer Scott: If Planet Nine is discovered, I'm confident a probe would eventually be sent to it! But after launch it might take decades for a spacecraft to reach that destination, so you'd have to be incredibly patient.*

In response to Philo: A small primordial black hole isn't impossible, but such objects remain theoretical, and as astronomer Mike Brown noted in my article, it's far more likely that Planet Nine is just a difficult-to-find planet. It might be one that's so dim that it doesn't reflect much light.

Regarding Kirsch's question: I think a brown dwarf is simply too massive to explain the gravitational perturbances detected by astronomers. It's more likely to be a stealthy, lighter planet.

PLACEBO EFFECT AND THE VAGUS NERVE

"Untangling the Vagus Nerve," by Jena Pincott, prompts a question: Does the vagus nerve itself orchestrate the placebo effect?

RICHARD BUCHANAN *LONDON*

PINCOTT REPLIES: *This inquiry raises an intriguing question. There is certainly a case to be made that the vagus nerve plays a role—directly or indirectly—in the placebo response. The*

expectation of an effective treatment could conceivably activate vagal pathways that influence various parts of the body, including the heart and gut, which in turn communicate with the brain. Seen this way, the placebo effect is not "all in the head" but instead involves deeper physiological mechanisms than previously understood.

With respect to vagus nerve stimulation (VNS) for major depression, however, its effects on successfully treated patients appear to extend beyond placebo. Whereas the placebo responses tend to kick in quickly but are short-lived, VNS has been shown to induce gradual, cumulative improvements that persist over years of treatment. Moreover, neuroimaging studies for both VNS and transcutaneous VNS have shown changes in brain regions that didn't occur in sham treatments. Future research should deepen our understanding of how the vagus nerve contributes to placebo effects while driving lasting physiological changes.

TILING SHAPES

In "Tessellation Revelation" [December 2024], Elise Cutts discusses mathematician Gábor Domokos's work on tiling "soft cell" shapes in two and three dimensions. Is there research into tiling in dimensions greater than three?

BRUCE BAKELY *SAN DIEGO, CALIF.*

The image of a 3D-printed soft cell derived from a hexagonal prism in Cutts's article bears a resemblance to the curvy lines of an ancient Egyptian artifact called the Sabu disk. Is that purely accidental?

REINHOLD SCHLIEPER *VIA E-MAIL*

CUTTS REPLIES: *Bakely is not alone in pondering four-dimensional soft cells. "We are often getting this question,"*

Domokos says. But he says his team hasn't set about answering it—yet. Other projects have the researchers' attention for now.

Regarding the Sabu disk: "This is stunning!" Domokos says. Because there is only a single example of the artifact, it's hard to say for sure why it has the geometry it does. But Domokos thinks there might be a reason the disk looks like a soft cell. Let's say you had a closed area with sixfold symmetry (like a regular hexagon) and wanted to turn its 2D curve into a 3D curve. If you tried to preserve as much of the boundary's symmetry as possible while keeping curvature to a minimum, Domokos says, you would end up with something like the Sabu disk's perimeter—and the boundary curve of the soft cell based on the hexagonal prism. Although it's a mystery what motivated the creators of the Sabu disk, "I think we acted under similar constraints and got similar results," Domokos says. "Beautiful!"

HUBBLE TENSION

"Cosmic Confusion," by Marc Kamionkowski and Adam G. Riess [November 2024], explores whether a new form of dark energy can resolve the so-called Hubble tension, the disagreement among estimates of how fast the universe is expanding. Can it be ruled out that dark energy is a force field produced by another nearby universe or even another universe that encloses ours?

JIM SULLIVAN *VIA E-MAIL*

Is it possible that the universe is spinning? If so, how would it do so? And could that affect the different expansion rates that have been observed, as if we were a slice of pepperoni on a pizza observing the pizza expand around us as it was tossed into the air?

CAMPBELL HODGSON *VIA E-MAIL*

THE AUTHORS REPLY: *Sullivan's interesting question would require more work to define and understand before it could be answered. People have indeed floated ideas about models with extra spacetime dimensions. There may be other universes that could be "near" our own in some of these extra spatial dimensions. We're not familiar with any work to implement these ideas in a solution to the Hubble tension, though.*

Hodgson brings up an excellent question, but we think the answer is no. In a spinning body, the speed at which something moves is proportional to its distance from the center. As physicists, we would say the universe is so big that even if it were spinning extremely slowly, there would be some distance at which things would be moving faster than the speed of light, which is not allowed. And observations so far support that the universe is uniform in all directions, which would preclude spinning.

CLARIFICATION

"The Astronaut Club," by Clara Moskowitz and Zane Wolf [Graphic Science; February], noted that Oliver Daemen became the youngest person in space at age 18 in 2021. He was 18.92 years old at the time and was followed by Anastatia Mayers, who went to space at the younger age of 18.87 years in 2023.

ERRATUM

In "Untangling the Vagus Nerve," by Jena Pincott, the graphic "Anatomy of the Vagus Nerve" incorrectly identified the pons of the brain stem as the medulla of the brain stem.

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

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Food

- ## A Perfectly Cooked Egg, according to Materials Science

  Materials scientists have found a way to perfectly cook an egg white and egg yolk simultaneously

How Do You Cook a Perfect Egg? Scientists Have Figured It Out

Materials scientists have found a way to perfectly cook an egg white and egg yolk simultaneously

By Arminda Downey-Mavromatis edited by Andrea Thompson & Sarah Lewin Frasier

vvmich/Alamy Stock Photo

Hard-boiling, soft-boiling or a trendy sous vide—no matter the approach, cooking a whole egg attains ideal texture for either the yolk or the white but rarely both. Now, however, scientists think they have cracked the perfectly cooked egg.

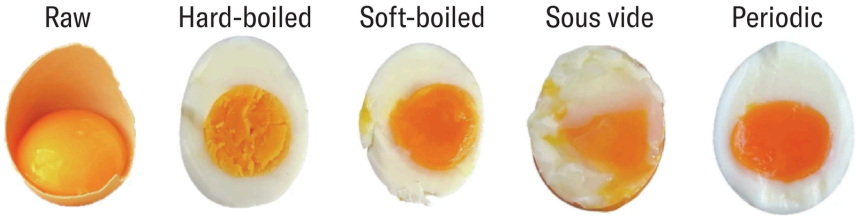
To trigger the optimal denaturation, or breakdown, of proteins while also keeping key nutrients intact, the ideal temperature for cooking an egg yolk is around 149 degrees Fahrenheit (65 degrees Celsius). For the egg white, or albumen, it's around 185 degrees F. Hard-boiling ensures the albumen is fully cooked, but it can yield a chalkier yolk. Soft-boiled eggs have a smoother yolk that can be too runny for some people's taste. A sous vide egg—cooked in water at 140 to 158 degrees F for at least an hour—is close to the

ideal. The resulting egg is creamy all the way through, but the albumen is only partially set. The necessary appliance is also not a common kitchen feature.

Materials science postdoctoral researcher Emilia Di Lorenzo and professor Ernesto Di Maio, both at the University of Naples Federico II in Italy, typically work on methods for making polymers with layers of different densities. But for a recent study in *Communications Engineering*, they sought a novel method for preparing an egg that would allow the yolk and egg white to cook optimally without being separated. “What we did in the case of eggs was to take this approach and try to get a layer of texture instead of a layer of densities,” Di Lorenzo says. Their inspiration was an €80 (about $87) egg dish in which the components cooked perfectly but separately.

Di Maio theorized that alternating an egg, still in its shell, between hot water and tepid water repeatedly for short periods would allow both yolk and albumen to reach their perfect form. The researchers used mathematical modeling and computer simulations to establish their alternating temperatures (212 and 86 degrees F), times (32 minutes total) and cycles (switching every two minutes). Then they cooked *a lot* of eggs to test their new method.

The team examined its results with Fourier transform infrared spectroscopy, which uses infrared waves to probe chemical structure, to find out how protein breakdown in the egg yolk and white had affected the texture of eggs that were hard-boiled, soft-boiled, cooked via sous vide or prepared with the new method.



The texture of an egg yolk and white when it is raw, hard-boiled, soft-boiled, cooked by sous vide, and cooked with the new "periodic" method.

Of course, when you are making eggs at home, you’re probably not ranking your preparation options based directly on the degree of protein denaturation—so the researchers further probed the overall texture and taste of the eggs with the help of some experts.

Texture profile analysis, which involves compressing pieces of egg, revealed that the hard-boiled egg’s albumen and yolk were harder and chewier than the other options but that the rest of the preparations were only subtly different. A panel of sensory experts assessed the eggs’ more subjective taste differences.

In the end, the team went through dozens upon dozens of eggs. There were “160 alone for the sensory analysis—personally cooked by Di Maio” in his kitchen, Di Lorenzo says.

The researchers found that if you’re looking to maximize your morning nutrition, their newly proposed “periodic” cooked egg may be the way to go. Nutrients were better preserved in the periodic eggs than in other preparations. “The most outstanding result was the preservation of polyphenols, but a lot of amino acids are preserved as well,” Di Lorenzo says. Amino acids are useful for building proteins in our body, and polyphenols are antioxidants that show promise as anti-inflammatory compounds.

The project changed Di Maio’s egg routines forever. Although he acknowledges that the preparation takes a bit longer than common kitchen methods, he’ll be periodic cooking going forward. Di Lorenzo, however, may not change her diet.

“We were really already deep into this egg project,” Di Maio says, when Di Lorenzo “told me that she doesn’t like eggs—at all.” But cracks are appearing in Di Lorenzo’s attitude. “Maybe,” she proposes, “this was a quest to try to like eggs.”

Arminda Downey-Mavromatis is associate engagement editor at *Scientific American*. She works on audience engagement, which includes managing *Scientific American*'s home page and social media, as well as engagement projects. Previously she was senior editorial project manager at *Chemical & Engineering News*, managing special issues of the magazine. She has a B.A. in biochemistry from Barnard College of Columbia University. While in undergrad, she was an editor at the *Eye*, the magazine of the Columbia Daily Spectator.

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| Section menu | Main menu |

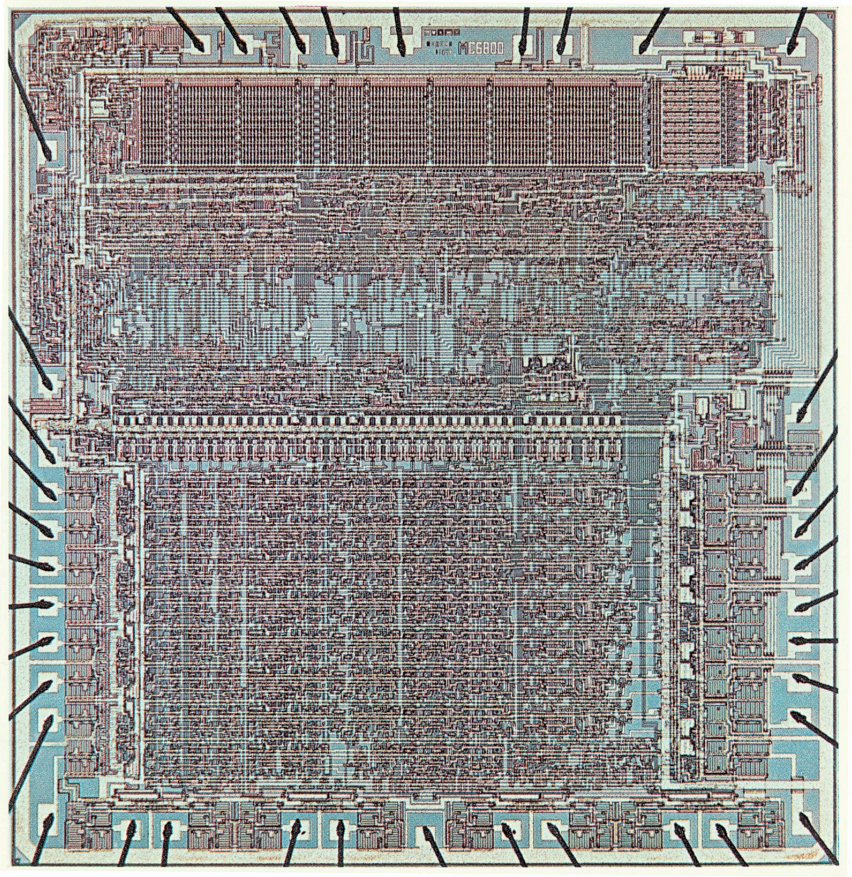
History

- **May 2025: Science History from 50, 100 and 150 Years Ago**
  Old-time graffiti; balloon deaths

May 2025: Science History from 50, 100 and 150 Years Ago

Old-time graffiti; balloon deaths

By Mark Fischetti



1975, Computer Chip: "Microprocessing unit if the Motorola microcomputer is an integrated circuit laid down on a single-crystal silicon chip 0.210 by 0.217 inch, enlarged in this image. The chip bears about 5,400 transistors. Black lines projecting outward are leads to pins of the finished package. In small lots the unit sells for $360."
Scientific American, Vol. 232, No. 5; May 1975

1975

Introducing the Videodisc

“A ‘videodisc’ system that presents recorded pictures and sound on a television set will be put on the market next year by North

American Philips Corporation and MCA Inc. The player looks somewhat like a phonograph, and the record resembles a phonograph record. The distinctive feature is an optical ‘stylus,’ which replaces the needle of the phonograph. The stylus is a scanner employing a one-milliwatt helium-neon laser as its sensor. The record is not touched by the playing device and therefore will not wear out or deteriorate. The optical stylus also makes it possible to pick out randomly part of a record for display, to run a scene in reverse or in slow motion, and to view a film frame by frame. The companies plan to sell the player for about $500 and the records for $2 to $10, depending on their length and content, which could include motion-picture films, instructional films, sports events and newsreels.”

A Giant Eye for Extraterrestrials

“Cyclops, an array of 1,500 radio antennas each 100 meters in diameter, has been proposed in a nasa-sponsored study as a tool for detecting signals from extraterrestrial civilizations. The antennas would be connected to one another and to a large computer system. The effective signal collecting area would be hundreds of times greater than that of any existing radio telescope and would be capable of detecting even such weak signals as the internal radio-frequency communications of a civilization as far away as several hundred light-years.”

The proposed Project Cyclops was shelved because of high anticipated costs.

1925

Colored Lights Reveal Speeding

“An idea has been suggested for a signal plate, firmly attached to a car, bearing three or four differently colored lights. These would be attached to the speedometer, so that the white light, for example,

would burn when the speed was 10 to 15 miles an hour, the blue light between 15 and 30, the red at 40, and so on. If any officer or citizen saw a car running on a street and burning a red light, that would be sufficient evidence that the speed limit was being exceeded to a dangerous extent. Something has to be done to make our streets safer."

Island Universes

"Thousands of universes, each similar to the galaxy of stars of which our sun is an insignificant member, with the nearest universe so distant that its light travels for a million years before it reaches us, have been shown to exist by Edwin P. Hubble, of the Mount Wilson Observatory. Through telescopes these universes appear to be clouds of light, more or less with a spiral structure. By means of variable stars in these galaxies, the distance of a few has been determined, and in the opinion of Harlow Shapley, director of the Harvard College Observatory, this proves the theory that they are 'island universes' lying entirely outside our own system."

Old-Time Graffiti

"Human nature is a pretty constant thing. Archeologists digging in the ruins at Sakkara have found columns which were once part of an ancient Egyptian temple. Over 3,000 years ago it was already a show place, a sort of Washington Monument of the time. On the columns are scribbled names and comments, written there by visitors of 30 centuries ago, just as people write their names and addresses on the walls of public buildings today."

1875

Balloon Deaths

"Croce-Spinelli and Sivel, two French aeronauts, have laid down their lives in the cause of science. With M. Gaston Tissandier, they

attempted to ascend to a higher altitude than had ever before been reached, to make experiments for carbonic acid, conduct spectroscopic observations, and in general obtain data. It was believed possible by inhaling oxygen from a respirator. At 29,000 feet elevation all three men became unconscious. The balloon soared higher and higher and then descended. Tissandier regained his senses on reaching respirable air, to find his companions dead from suffocation."

Mark Fischetti has been a senior editor at *Scientific American* for 17 years and has covered sustainability issues, including climate, weather, environment, energy, food, water, biodiversity, population, and more. He assigns and edits feature articles, commentaries and news by journalists and scientists and also writes in those formats. He edits History, the magazine's department looking at science advances throughout time. He was founding managing editor of two spinoff magazines: *Scientific American Mind* and *Scientific American Earth 3.0*. His 2001 freelance article for the magazine, "Drowning New Orleans," predicted the widespread disaster that a storm like Hurricane Katrina would impose on the city. His video *What Happens to Your Body after You Die?*, has more than 12 million views on YouTube. Fischetti has written freelance articles for the *New York Times*, *Sports Illustrated*, *Smithsonian*, *Technology Review*, *Fast Company*, and many others. He co-authored the book *Weaving the Web* with Tim Berners-Lee, inventor of the World Wide Web, which tells the real story of how the Web was created. He also co-authored *The New Killer Diseases* with microbiologist Elinor Levy. Fischetti is a former managing editor of *IEEE Spectrum Magazine* and of *Family Business Magazine*. He has a physics degree and has twice served as the Attaway Fellow in Civic Culture at Centenary College of Louisiana, which awarded him an honorary doctorate. In 2021 he received the American Geophysical Union's Robert C. Cowen Award for Sustained Achievement in Science Journalism, which celebrates a career of outstanding reporting on the Earth and space sciences. He has appeared on NBC's Meet the Press, CNN, the History Channel, NPR News and many news radio stations. Follow Fischetti on X (formerly Twitter) @markfischetti

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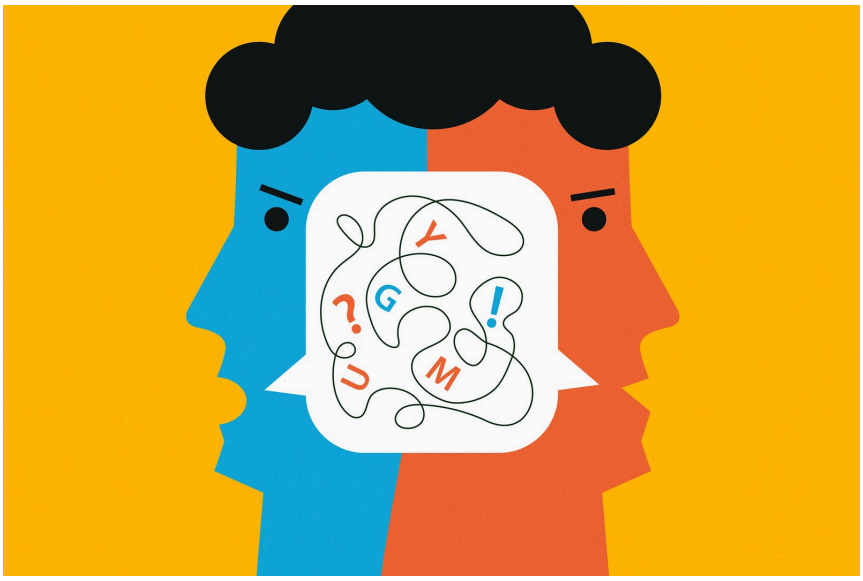
Language

- **Does Your Language’s Grammar Change How You Think?**
  The brain’s response to information depends on language’s grammatical structure
- **Science Crossword: Hidden Figures**
  Play this crossword inspired by the May 2025 issue of Scientific American

Language Differences Control Your Brain's Sentence-Prediction Habits

The brain's response to information depends on language's grammatical structure

By Gayoung Lee edited by Sarah Lewin Frasier



Jiri Studnicky/Getty Images

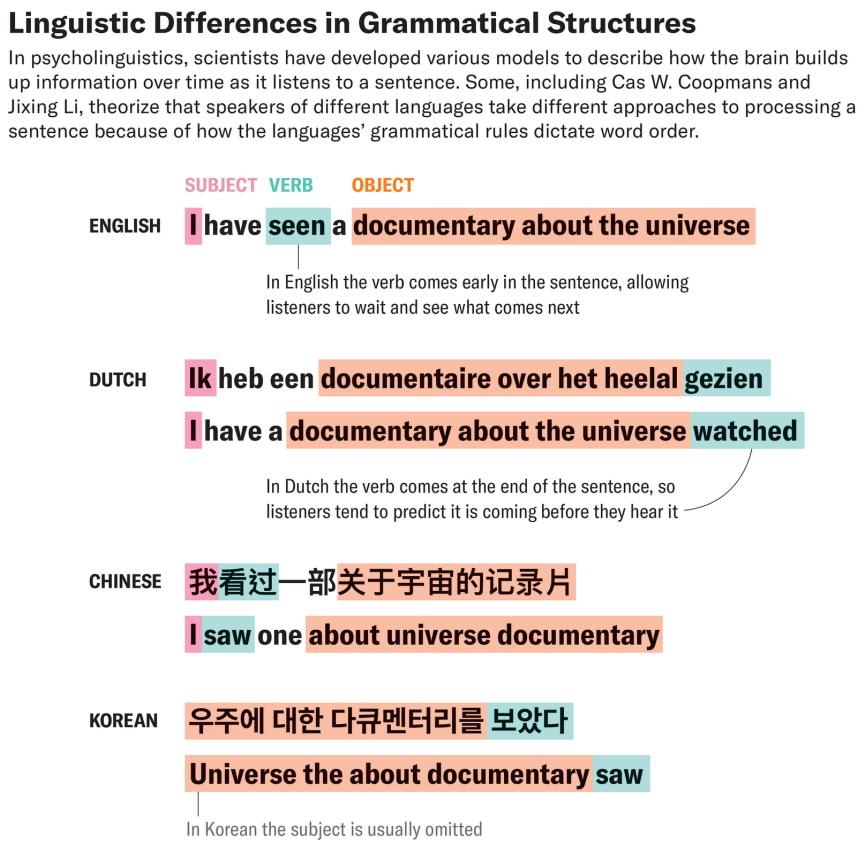
Understanding a simple-looking sentence such as "I read this article yesterday" actually requires some sophisticated conceptual computation: a subject ("I") performed an action ("read") on an object ("article") at a specific time ("yesterday"). But the human brain routinely does this work nearly instantaneously based on the language's grammatical rules, says linguist Andrea E. Martin of the Max Planck Institute for Psycholinguistics in the Netherlands. And Martin's team has now found that the human brain accommodates fundamental grammatical differences across languages by adjusting how it processes each sentence.

For a recent study in *PLOS Biology*, the researchers observed variations in Dutch-speaking participants' brain waves while they

listened to a Dutch-language audiobook. To visualize these changes, the scientists used a metric quantifying how many new “predictions” the brain makes of words that could come next in a sentence. This framework was then tested against three different parsing strategies, or linguistic models that illustrate how the brain builds information over time.

Previous English-based studies with a similar setup concluded in favor of a model where listeners “wait and see” how each phrase in a sentence will end before interpreting it. But the Dutch speakers in Martin’s study leaned strongly toward a highly predictive model; participants tended to preemptively finish each phrase in their head before it was complete. (A third model, in which listeners wait to hear all the phrases in a sentence before interpreting any part of it, is seldom used in either language.)

In Dutch language structure, verbs sometimes come near the end of a sentence rather than immediately after the subject like they do in English, explains study lead author Cas W. Coopmans, a postdoctoral researcher in New York University’s department of psychology. For instance, “‘because I ate a cookie with chocolate’ in Dutch would be ‘because I a cookie with chocolate ate.’ You would have to wait very long for the verb to come,” Coopmans says. “And that’s probably unrealistically late; you’re probably much more predictive in processing” the sentence.*



Ripley Cleghorn

Neither parsing strategy is necessarily "better or worse" than the other, Coopmans adds. "It just happens to be suited to the language [people] are processing. So we seem to be quite flexible in that you might process one language differently from another simply because they have different properties."

The findings support the need for scientists to incorporate more diversity when crafting linguistic models, says Jixing Li, a linguist at City University Hong Kong, who was not involved in the new study. Her own work has illustrated how different brain regions activate when processing English or Chinese sentences because of their differing linguistic properties. If these studies are done only in neurotypical English-speaking adults, she says, crucial differences in processing will be missed. Li contends that this limitation defeats the purpose of the models, which are meant to provide a realistic picture of human language-based thinking.

Diversifying subjects in studies of how the brain processes language “is going to help us capture how the brain is [understanding] the structured meaning of language, and the social utility of language, in many different ways,” Martin says. “There’s so much yet to be understood in the brain.”

**Editor's Note (4/14/25): This paragraph was edited after posting to correct the descriptions of Dutch language structure.*

Gayoung Lee is *Scientific American*’s current news intern. 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/does-your-languages-grammar-change-how-you-think

Science Crossword: Hidden Figures

By Aimee Lucido

This crossword is inspired by the May 2025 issue of Scientific American. *Read it here.*

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-hidden-figures

Marijuana

- **The Link between Cannabis and Psychosis in Teens Is Real**
  Teens have access to vastly more potent cannabis than their parents had at their age. Parents need to understand the risks, including psychosis

The Link between Cannabis and Psychosis in Teens Is Real

Teens have access to vastly more potent cannabis than their parents had at their age. Parents need to understand the risks, including psychosis

By Carrie E. Bearden edited by Megha Satyanarayana

Malte Muller

Sam’s father sat slumped on the leather couch in the clinical interview room, head in his hands. He had just finished telling the long, painstaking history of his son’s descent into psychosis. Sam (whose name has been changed to protect his confidentiality), then 17, had started casually using marijuana with friends in the ninth grade. He “dabbled” with other substances as well (Xanax, Ecstasy), but he used cannabis most consistently.

Sam’s father told me that he and his wife had used cannabis themselves a fair amount in college and were inclined to agree with their son when he told them, “Don’t worry, it’s just pot!” They

pleaded with him to buy it from cannabis shops rather than getting it “on the street.”

In California, where I work as a researcher and clinician studying the links between cannabis use and psychosis, it is not difficult to get a medical marijuana card, even for a teenager.

Sam started high school as a fairly good student with several friends. Over time he began using cannabis daily. He took it a variety of ways, first with friends at parties and then, more and more often, alone. His parents noticed increasingly odd behavior: He blocked the camera on his laptop and placed cardboard over the windows in his room. He stopped showering. He began refusing to go to school. Against Sam’s will, his parents took him to a rehab facility for teens. During the three-week program he was fully abstinent from cannabis, but, disturbingly, his psychotic symptoms got worse rather than better; simply stopping wasn’t enough for Sam to recover.

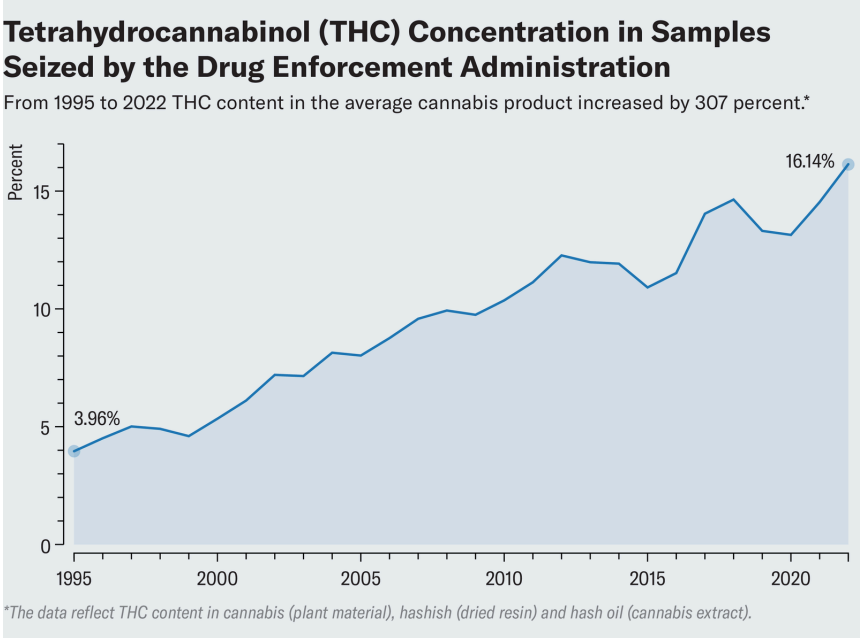
By the time his family came to my clinic, he had had persistent delusions for more than six months. Sam was fully convinced that the government was following him and constantly surveilling him. Although we don’t know whether cannabis caused Sam’s psychosis, it was striking that his symptoms didn’t go away when he stopped using. It is possible cannabis had altered his brain function.

Modern-day cannabis is simply not the same as the plant used in the 1960s through the 1980s or even as recently as 10 years ago. New strains of cannabis are highly potent, making them more addictive and potentially more dangerous, and we are still trying to understand what the drug does to developing adolescent brains. As a scientist and a parent, I recommend that people avoid using cannabis until at least their mid-20s, but I realize this advice may not be realistic. If your teens are going to use today’s cannabis, it is critically important that you be aware of the data showing what a

different beast this substance has become and the risk of major mental health issues it poses.

All cannabis products contain a mix of delta-9-tetrahydrocannabinol (THC), the intoxicating component of the cannabis plant, and cannabidiol (CBD), which may have anxiety-reducing properties. In the 1990s the marijuana in a typical joint contained about 5 percent THC.

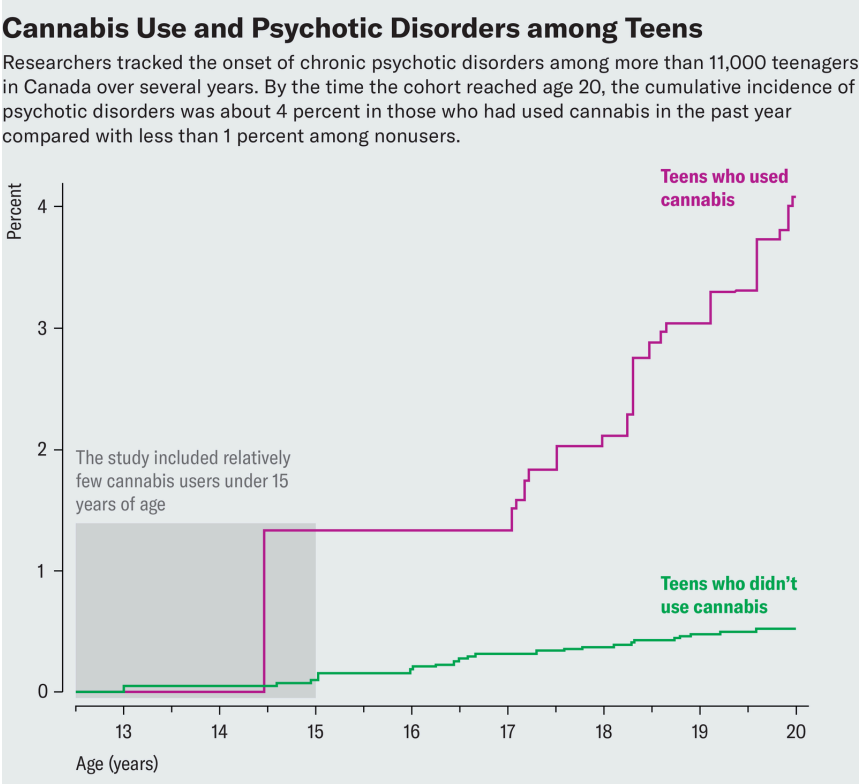
But genetic modification has drastically increased THC potency; from 1995 to 2022 its content in the average cannabis plant increased by 307 percent. And it's not just joints or pot brownies; with the expanding legalization and commercialization of cannabis, there are few limits on the levels of THC in products such as fast-acting vape pens and edibles. What Sam and other teens can buy today is nothing like what their parents used in college.



Ripley Cleghorn; Source: Cannabis Potency Data, National Institute on Drug Abuse

Higher-potency THC, marijuana use starting at a young age and more frequent use all increase the risk of psychosis. A Canadian research team studying more than 11,000 teens found that compared with nonusers, cannabis users faced an 11-fold increase in the risk of developing a psychotic disorder. In light of such

daunting data, some researchers have begun sounding the alarm. But we are struggling to get this information to those who need to hear it most: parents, educators and legislators. And although there isn't a clear consensus that cannabis causes psychosis, studies like the ones I've mentioned, which are well designed and carefully analyzed, indicate that the two things are associated.



André J. McDonald, modified and restyled by Ripley Cleghorn; Source: "Age-Dependent Association of Cannabis Use with Risk of Psychotic Disorder," in *Psychological Medicine*, Vol. 54, No. 11; August 2024

Another big question we are trying to answer: Why is the increased risk of psychosis so profound in teens? The researchers in my field think it has something to do with the significant rewiring that happens in adolescent brains, which continues into our early 20s, when symptoms of psychotic disorders typically start showing up. The same molecules and receptors in our brains that interact with THC (known as the endocannabinoid system) play an essential role in brain development. And there is growing evidence from both animal and human studies that early cannabis exposure can disrupt the way brain cells, or neurons, respond to what we experience and

how they communicate with one another to make those experiences memories.

So how do you talk to your kids about cannabis? When families come to my clinic for youth at risk for psychosis, my colleagues and I ask the kids why they use cannabis and how they feel afterward. We ask them why they might stop using and whether they could stop if they needed to. And then: Why not try stopping for a few days and see how you feel? The answers help us assess whether the person has a cannabis addiction.

Some teens tell us they can stop. But others aren't willing. For them, we recommend that they avoid high-potency products and instead choose products with higher CBD-to-THC ratios.

If you have a teenager at home or will soon, the odds are that they are going to be exposed to a lot of cannabis in many forms—at school, at parties, all around the neighborhood. It is never too early to have that conversation. To get ready for it, make sure you have good "cannabis literacy." The National Institute on Drug Abuse is a good place to start. Encourage your child to seek out reputable sources of information, too, rather than believing what they hear from friends or see on social media. It can be helpful to set clear rules and boundaries around cannabis use that you all agree on and establish what the consequences are for breaking those rules. Parents should foster clear, nonjudgmental communication about use and assure their children that it's okay for them to share their questions and concerns.

For Sam, we recommended ongoing psychiatric treatment and family therapy, which his parents found valuable given that their son was living with a chronic psychotic disorder. If your child starts experiencing worrisome symptoms or engaging in unusual behaviors—such as isolating themselves from others, talking to themselves, or hearing or seeing things that other people don't—seek psychological treatment right away. Your family physician or

child’s pediatrician can provide a referral to a specialist for an evaluation and treatment.

Like so many things our children are exposed to now, the vastly changed landscape of cannabis products and their availability is an experiment none of us consented to in an informed way. The best we can do is try to make our retroactive consent (and that of our kids) as informed as possible.

Carrie E. Bearden is a professor of psychiatry, biobehavioral sciences and psychology at the University of California, Los Angeles. She directs a clinical research program focused on early intervention for psychosis spectrum disorders in young people (https://capps.semel.ucla.edu). Follow her at @carriebearden.bsky.social

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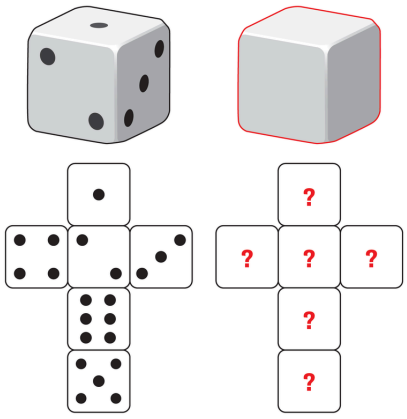
Mathematics

- **Math Puzzle: Construct the Dice**
  Build a special set of dice in this math puzzle
- **Mathematical Symbols' Wild History Explained**
  A mathematician has uncovered the stories behind the symbols used in math
- **Mathematicians Solve Infamous 'Moving Sofa Problem'**
  What's the largest couch that can turn a corner? After 58 years, we finally know

Math Puzzle: Construct the Dice

By Hans-Karl Eder

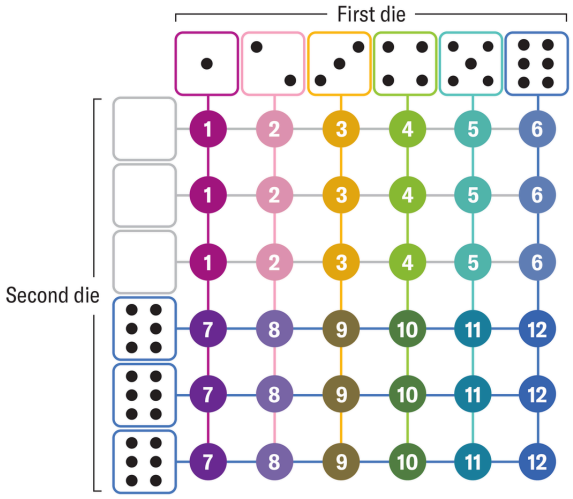
Marie has one regular die labeled with the numbers 1, 2, 3, 4, 5 and 6 and a second cube that is completely blank. She labels this cube in a special way. If you roll both dice, you can get the following totals: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12. The special part: all 12 total values are equally likely to be rolled. How did Marie label the cube?



Amanda Montañez

The sides of the die must be labeled 0, 0, 0, 6, 6 and 6.

There are 36 possible totals when rolling two dice. If the 12 sum values are all to have the same probability, then each value must occur exactly three times.



Amanda Montañez

The total value of 12 can be achieved with two dice only if both dice show a 6. Because the value 12 must appear three times in the table, the cube Marie labels must have three sides with a 6. The rest of the needed results are possible only if the other three sides are labeled with a 0.

For each sum value from 1 to 12, the probability *p* is

$p = 3 / 36 = 1 / 12 \approx 8.3\%$

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

This puzzle originally appeared in Spektrum der Wissenschaft *and was reproduced with permission.*

Hans-Karl Eder is a German mathematician, educator and author who also works as a MINT ambassador to get young people interested in mathematics, computer science, natural sciences and technology.

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https://www.scientificamerican.com/article/math-puzzle-construct-the-dice

The Wild and Contentious History of Mathematical Symbols

A mathematician has uncovered the stories behind the symbols used in math

By Max Springer edited by Clara Moskowitz

Shideh Ghandeharizadeh

War in Europe is a staple topic in the study of history, but there's one major conflict most history books won't teach you: the battle of the equal sign, =. These two parallel lines were, in fact, the source of serious dispute among European mathematicians in the mid-1500s. This dispute is just one of many such little-known events; for example, another debate has been raging for centuries over who invented the symbol for zero, 0. In *The Language of Mathematics: The Stories behind the Symbols* (Princeton University Press, 2025), author and mathematician Raúl Rojas explores these and other examples of the complex, and sometimes uncertain, history of mathematical symbolism.

Over the years competing camps have considered adopting one or another notation for many different aspects of mathematics. Rojas guides us along the historical arc of mathematics, intertwining its evolution with the cultural, philosophical and practical needs of the societies that shaped and relied on it.

Scientific American spoke to Rojas about this chronology, the deeply engaging humanity of mathematics, and the egos at play in defining the mathematical language we take for granted today.

An edited transcript of the interview follows.

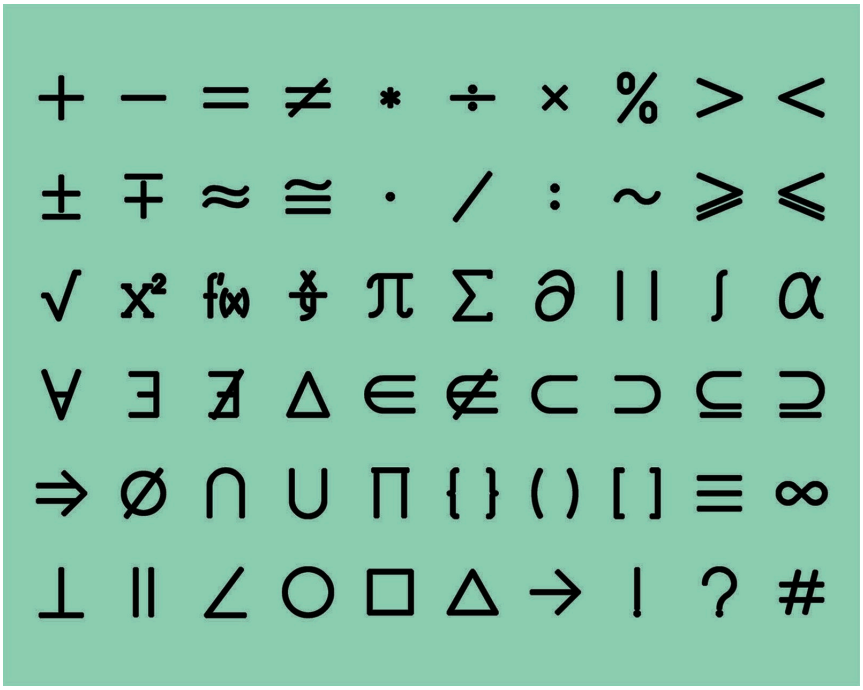
What inspired you to write this book about the stories behind these symbols?

I started teaching in 1977, and across my nearly 50 years I noticed that students were always interested in the history of mathematics. When you teach linear algebra or calculus, it's important to tell students about the people who developed the concepts and how those concepts came to be. I started doing seminars on the history of mathematical notation, and I had every student study one symbol and explain its origin. I found that those students who are falling asleep in class suddenly wake up when you add a human story behind the abstract symbols.

Throughout the book, you discuss symbols that ultimately failed to become the standard en route to the notation we know today. How were these things decided?

One of the interesting things about the history of mathematical notation is its regional variation over the centuries. There was one kind of notation in Italy, another in Germany, the U.K. and France. All these different regions were producing symbols, and with the advent of the printing press, there was an explosion of proposals. So how did it happen that a single symbol could become standardized?

One good example is the symbol of equality, =. This relation was mostly expressed with words in the beginning. Later René Descartes in France started using a rotated Taurus symbol, α, and Gottfried Wilhelm Leibniz in Germany used a wedgelike shape. And before Descartes and Leibniz, Robert Recorde in the U.K. invented the equal sign we use today, though in an elongated form. Mathematicians found themselves in a kind of battle over arithmetical symbols based on popularity. A notable contest was between + and − versus p and m, which the Italians preferred for denoting operations. Eventually the plus and minus signs became universal, as did the English symbol for equality, but only after decades of famous mathematicians competing in these popularity contests to set the trends.



Nadiinko/Getty Images

Is there a particular symbol in the history of mathematics that significantly influenced how we think about abstract concepts?

There is one symbol, which has an incredibly long history that has not yet been fully written: 0. How did it arise? We know it was used by the Babylonians, but they didn’t write a 0 as we know it. They worked with a positional base-60 system and simply left a

blank where we would write 0 today. This was their natural way of showing zero: if it's nothing, then you don't have to write anything.

Later, through the conquests of Alexander the Great, the Greeks took the positional number system to India, where we believe the Hindu culture developed the first representation of 0. There's a friendly competition among anthropologists working to find the oldest instances of 0 in writing. Every five or six years someone finds an older engraving. It's fascinating because this simple symbol we use every single day without thinking about it has a history that encompasses thousands of years.

You describe Gerhard Gentzen's "for all" symbol (∀) as a "cubist tear flowing from an eye that Picasso could have painted." What's the story behind that notation?

Gentzen's life is deeply tragic to me. He was an exceptional mathematician who, like many others in Nazi Germany, compromised with the regime. Although he was never a political person, he became a member of the Nazi Party and later joined the SS—the most criminal arm of the regime. Absorbed in his work, he did these things to advance his career. Even after the war, he expressed no guilt, claiming he was neither a soldier nor doing anything wrong. He had taken a position at the University of Prague, however, displacing others under Nazi occupation. Ultimately he chose not to flee after the war, was captured and died of starvation in prison.

There is no excusing his actions, but his life remains tragic from beginning to end, especially when considering what he might have accomplished had he taken a different path. It's fascinating that such a simple symbol—this upside-down A—carries such a complex and poignant history.

What do you hope readers—especially those outside the math community—might take away from your book?

It’s important to understand that mathematics is a historical process, just like any social science or politics. Mathematics didn’t arise complete and finished through the work of just one mathematician; it has a cultural history that spans many years. For centuries we’ve been looking at the sky or computing. In school, they teach addition and multiplication but rarely explain the origins or history of the symbols. This vast history is untold, but the excitement of doing mathematics comes from this knowledge that you are building on a framework developed by fascinating people over thousands of years.

Max Springer is a Ph.D. candidate in applied mathematics at the University of Maryland and was a 2024 AAAS Mass Media Fellow at *Scientific American*.

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https://www.scientificamerican.com/article/mathematical-symbols-wild-history-explained

Mathematicians Solve Infamous ‘Moving Sofa Problem’

What’s the largest couch that can turn a corner? After 58 years, we finally know

By Jack Murtagh edited by Jeanna Bryner & Madhusree Mukerjee

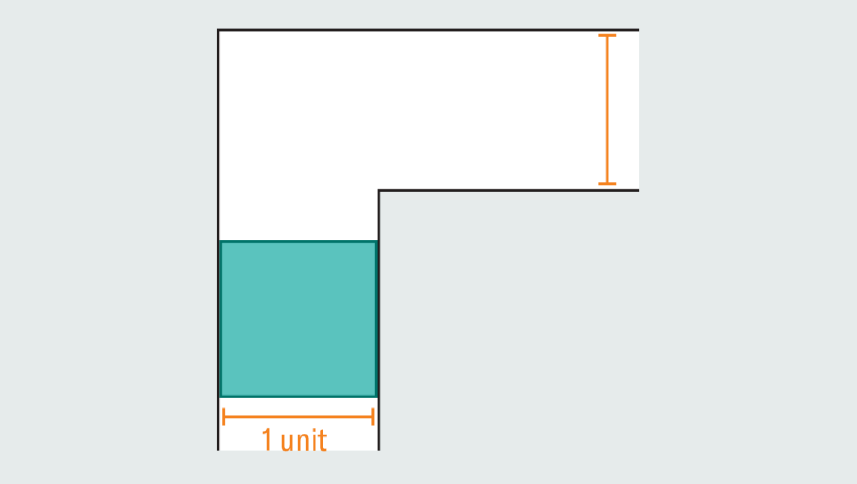
Thomas Fuchs

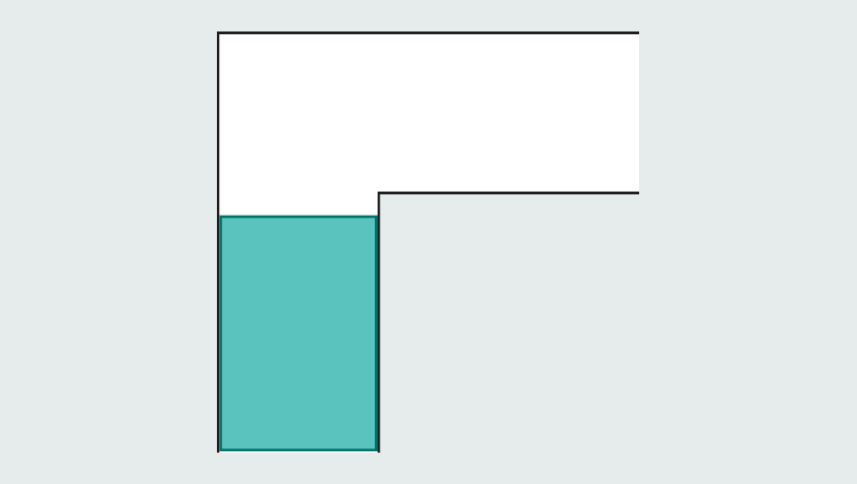
For those who have wrestled a bulky couch around a tight corner and lamented, “Will this ever get through?” mathematicians have heard your pleas. Geometry’s “moving sofa problem” asks for the largest shape that can turn a right angle in a narrow corridor without getting stuck. The problem sat unsolved for nearly 60 years until November 2024, when Jineon Baek, a postdoctoral researcher at Yonsei University in Seoul, posted a paper online claiming to resolve it. Baek’s proof has yet to undergo thorough peer review, but initial comments from mathematicians who know Baek and the moving sofa problem seem optimistic. Only time will tell why it took Baek 119 pages to write what Ross Geller of the sitcom *Friends* said in one word: “Pivot!”

The solution is unlikely to help you on moving day, but as frontier math grows more abstruse, mathematicians hold a special fondness for unsolved problems that anybody can understand. In fact, the popular math forum MathOverflow maintains a list of "not especially famous, long-open problems which anyone can understand," and the moving sofa problem currently ranks second on the list. Still, every proof expands our understanding, and the techniques used to resolve the moving sofa problem will probably lend themselves to other geometric puzzles down the road.

The rules of the problem, which Canadian mathematician Leo Moser first formally posed in 1966, involve maneuvering a rigid shape—meaning that the sofa's ends don't yield when pressed—to turn at a right angle in a hallway. The "sofa" can be any geometric shape; it doesn't have to resemble a real couch. Both the shape and the hallway are two-dimensional. Imagine the sofa weighs too much to lift, and you can only slide it.

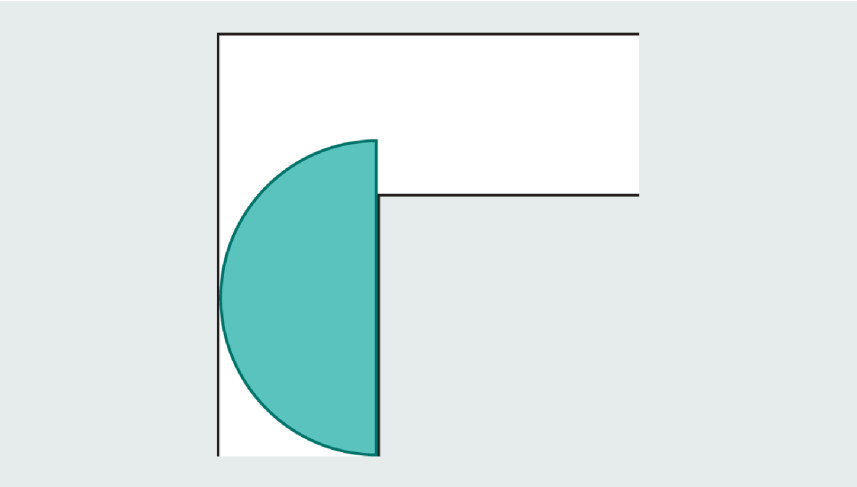
A quick tour through the problem's history reveals the extensive effort that mathematicians have poured into it—they were no couch potatoes. Faced with an empty hallway, what is the largest shape you could squeeze through it? If each leg of the corridor measures one unit across (the specific unit doesn't matter), then we can easily scoot a one-by-one square through the passage. Elongating the square to form a rectangle leads to instant failure because when the object hits the kink in the hallway, it has no room to turn.





Amanda Montañez

Yet mathematicians realized they could go bigger by introducing curved shapes. Consider a semicircle with a diameter (along its straight base) of two units. When it hits the turn, much of it overhangs in the first leg of the hallway, but the rounded edge leaves just enough room to clear the corner.



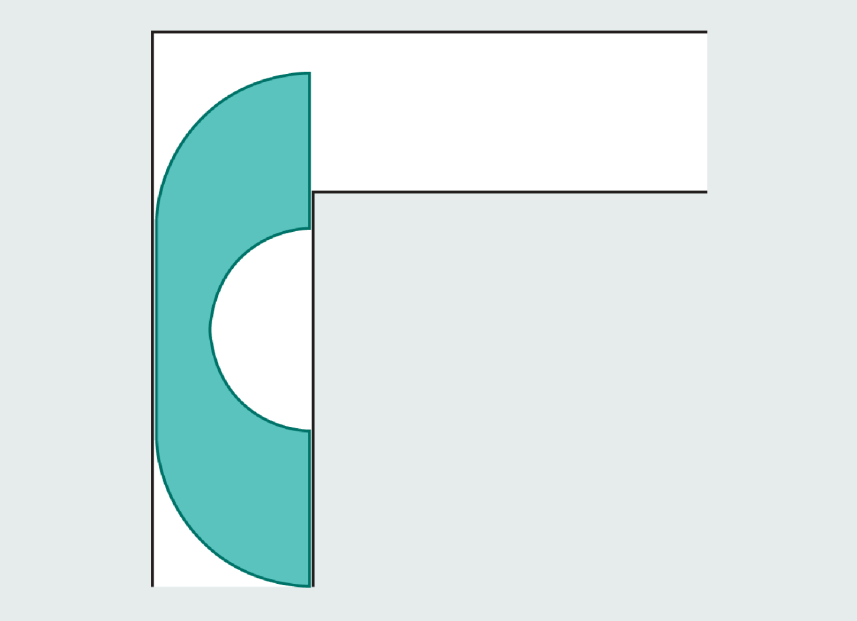
Amanda Montañez

Remember the goal is to find the largest “couch” that can slide around the corner. If we dust off our high school geometry formulas, we can calculate the area of the semicircle as $\pi/2$, or approximately 1.571. The semicircle is a significant improvement over the square, which had an area of only one unit. Unfortunately, both would look strange in a living room.

Solving the moving sofa problem requires that you optimize not only the size of a shape but also the path that shape traverses. The

setup permits two types of motion: sliding and rotating. The square couch only slid, whereas the semicircle slid, rotated around the bend and then slid again on the other side. But objects can slide and rotate at the same time. Mathematician Dan Romik of the University of California, Davis, has noted that a solution to the problem should optimize both types of motion simultaneously.

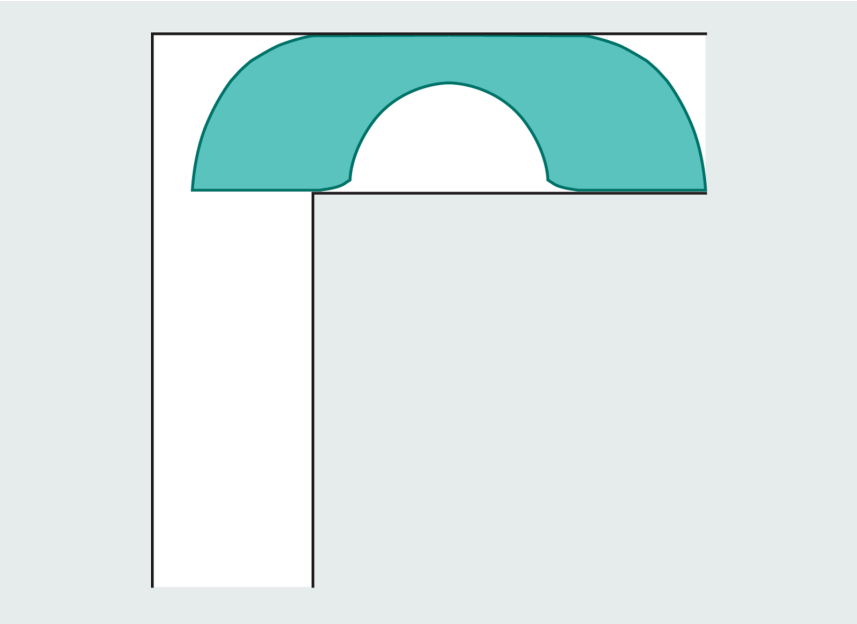
British mathematician John Hammersley discovered in 1968 that stretching the semicircle can give you a larger sofa if you carve out a chunk to deal with that pesky corner. Furthermore, Hammersley's sofa takes advantage of a hybrid sliding-plus-rotating motion. The resulting sofa looks like the handset of a landline phone.



Amanda Montañez; Source: "On Moving a Sofa Around a Corner," by Joseph L. Gerver, in *Geometriae Dedicata,* Vol. 42, No. 3; June 1992 (*reference*)

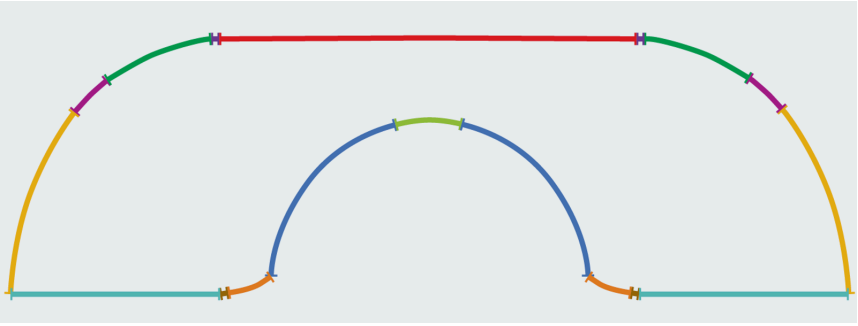
Optimizing the different variables yields a sofa with area of $\pi/2 + 2/\pi$, or approximately 2.2074. This is a huge upgrade from the semicircle, akin to moving from a love seat to a sectional. But progress stalled there for 24 years. The next significant improvement would be the last. In 1992 Joseph L. Gerver of Rutgers University unveiled a masterwork of mathematical carpentry, which we now know to be the largest possible sofa.

At first Gerver's sofa might look identical to Hammersley's, but it's a much more complicated construction. Gerver stitched together 18 distinct curves to form his shape. On closer inspection, you might spot some differences, especially the beveled edges at the base of the rounded cutout.



Amanda Montañez; Source: "On Moving a Sofa Around a Corner," by Joseph L. Gerver, in *Geometriae Dedicata*, Vol. 42, No. 3; June 1992 (*reference*)

The area of Gerver's triumph measures 2.2195 units. Surprisingly, Hammersley's relatively simple sofa fell only about 0.012 short of the optimal size. Although Gerver's discovery is just a skosh larger than its predecessor, Gerver suspected that he had identified the maximum possible size. He couldn't prove it, though. And neither could anybody else for another 32 years.



Amanda Montañez; Source: "On Moving a Sofa Around a Corner," by Joseph L. Gerver, in *Geometriae Dedicata*, Vol. 42, No. 3; June 1992 (*reference*)

In the absence of proof, several researchers turned to intensive computer simulations, which demonstrated new bounds on the largest sofa that could traverse the corner. Baek was at the forefront of these efforts, which made it all the more surprising that his eventual solution did not rely on computers at all.

Baek wrote his Ph.D. thesis on the moving sofa problem, contributing several incremental insights. That same year he sewed all his fresh ideas together into an impressive opus that proves no sofa larger than Gerver's can squeeze through the hallway. Cracking a long-standing open problem is a dream for any mathematician, let alone one so early in their career. If Baek's work withstands scrutiny, he will most likely find himself in high demand for professorships. Unless he pivots into furniture making.

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

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https://www.scientificamerican.com/article/mathematicians-solve-infamous-moving-sofa-problem

Mental Health

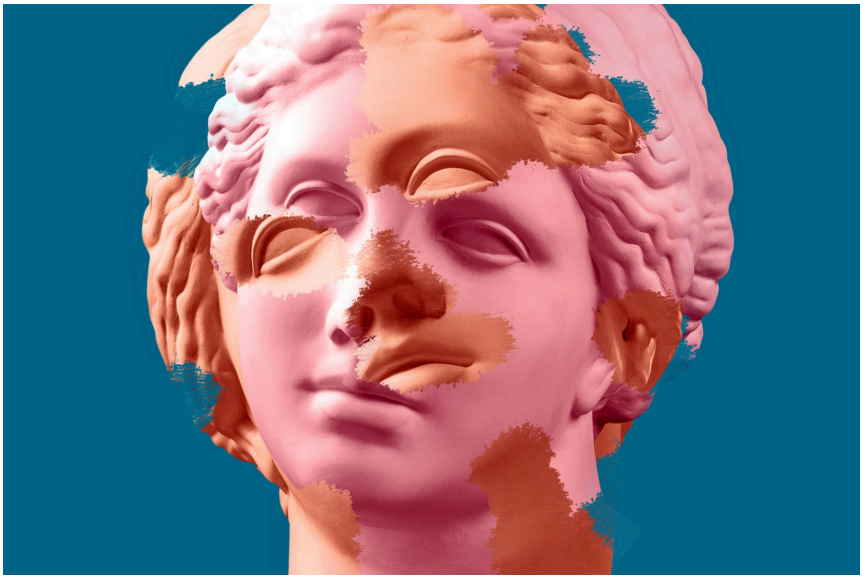
- ## ADHD Symptoms Can Fluctuate with the Menstrual Cycle

  Attention deficit hyperactivity disorder symptoms worsen right before and during a period, a new study finds, and this could affect treatment

How Menstrual Periods Can Affect ADHD Symptoms and Treatment

Attention deficit hyperactivity disorder symptoms worsen right before and during a period, a new study finds, and this could affect treatment

By Kelso Harper edited by Tanya Lewis & Sarah Lewin Frasier



Bashta/Getty Images

Researchers once thought of attention deficit hyperactivity disorder (ADHD) as an unchanging condition: either you have it or you don’t, end of story. But it’s become clear that ADHD symptoms can change across a person’s lifespan, and now research shows that symptoms can even shift over the course of a menstrual cycle.

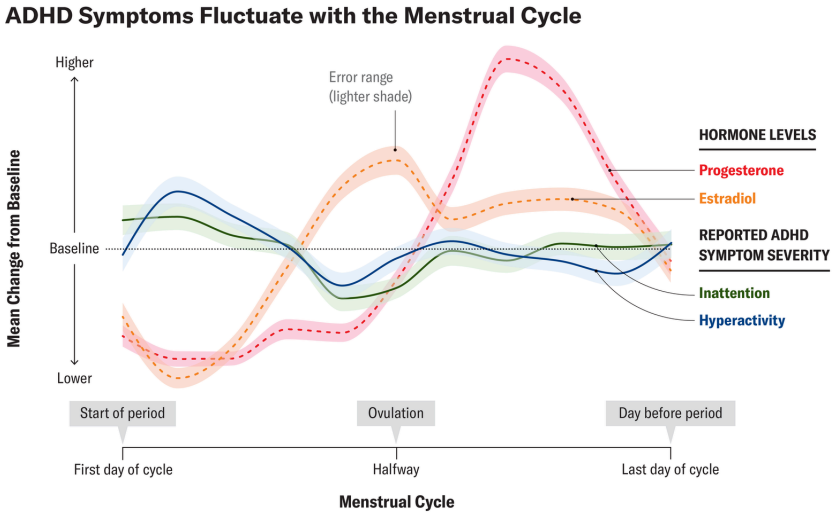
The new findings, which were presented at the U.S. Psychiatric and Mental Health Congress but have not yet been published in a peer-reviewed journal, provide the strongest evidence so far that ADHD symptoms can fluctuate along with hormonal shifts.

“It gives us a personalized insight into what is happening for many women with ADHD,” says Dora Wynchank, a psychiatrist and

researcher at Dutch mental-health-care organization PsyQ, who was not involved in the study. “Because ADHD historically has been studied in boys and men, we’ve missed out on this very important aspect.”

Michelle Martel, a clinical psychologist and chair of the psychology department at the University of Kentucky, led the research, which followed 97 female college students across their menstrual cycle. Nearly all participants had a formal ADHD diagnosis, and roughly half took psychostimulants for treatment. Martel’s team measured participants’ hormone levels every day and assessed their ADHD symptoms with questionnaires and cognitive tests.

Martel and her colleagues found that participants reported worse ADHD symptoms, such as inattention and impulsivity, just before and at the start of their period and, to a lesser extent, around ovulation. This aligned with the results of cognitive tasks, and it also echoes what many psychologists, including Martel and Wynchank, have already heard from their patients.



Ripley Cleghorn; Source: ADHD in Adult Women: Challenges and New Directions,” by Michelle M. Martel. Presented at Psych Congress, Boston, November 2024 (*data*)

Wynchank says clients have told her that “something happens to me in the week before my period when all hell breaks loose. A

couple days into my period, I look back, and I don’t recognize myself. And this comes back every month.”

Martel says these changes appear to be largely caused by drops in estradiol, the most powerful form of estrogen. Estrogen is mostly known as a sex hormone, but it’s also active in the brain, aiding in attention, memory and mood stabilization. Plus, it helps the body produce and maintain levels of dopamine, an important brain-signaling chemical that plays a central role in ADHD.

“It’s about a sensitivity to hormonal fluctuations,” Wynchank hypothesizes. “That combination of poorly operating dopamine and low levels of estrogen is just a sort of double whammy that makes the cognitive symptoms so much worse.” This interaction might explain why studies show higher rates of premenstrual dysphoric disorder—a severe form of premenstrual syndrome—in people with ADHD, as well as a higher likelihood of postpartum depression and worsened perimenopause symptoms. Estrogen levels are known to drop before menstruation, after a person gives birth and around menopause.

Martel’s newest results show the same effect seen in her 2018 preliminary study of 32 participants. “It’s really just verifying everything we found before,” Martel says. “It really does allow us to trust that these results are accurate, that we’re picking up on something real.”

The findings could redirect the diagnosis and treatment of ADHD. In Martel’s preliminary study, some participants met the criteria for ADHD only at certain points in their menstrual cycle, which could affect their ability to be diagnosed. And Martel wants to explore whether some people would benefit from cyclical adjustment to their ADHD medication.

Wynchank and her collaborators published a case study in 2023 that supports this idea of a cycle-specific prescription. The

researchers prescribed an increased premenstrual dose of ADHD medication to nine of their patients and followed them for six months to two years. All participants reported improved symptoms without increased side effects and planned to continue the titrated dose. Wynchank notes that other measures, such as psychotherapy and hormonal birth control, may help with worsened premenstrual ADHD symptoms, but they haven't yet been studied in depth.

Both Wynchank and Martel agree that a lot of work remains to be done in this area. "ADHD is definitely dramatically understudied in girls and women," Martel says. To combat this disparity, Wynchank and her collaborators are currently conducting a worldwide survey of women with ADHD. "We want to know what the lived experience is for women with ADHD and what their research priorities are," Wynchank says. "It's not about what we're interested in researching. We want that to come from the women themselves."

Kelso Harper is an award-winning senior multimedia editor at *Scientific American*. As a producer, editor and host, they work on short documentaries, social videos and *Scientific American*'s podcast *Science Quickly*. They have a bachelor's degree in chemistry from Johns Hopkins University and a master's degree in science writing from the Massachusetts Institute of Technology. Previously, they worked with *Wired*, *Science*, *Popular Mechanics*, and *MIT News*. Follow them on LinkedIn and Instagram.

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https://www.scientificamerican.com/article/adhd-symptoms-can-fluctuate-with-the-menstrual-cycle

Neuroscience

- **‘Artificial Nap’ Could Provide Benefits of Sleep—Without Sleeping**
  Desynchronizing a monkey’s brain with electricity caused a performance boost

‘Artificial Nap’ Could Provide Benefits of Sleep—Without Sleeping

Desynchronizing a monkey’s brain with electricity caused a performance boost

By Simon Makin edited by Sarah Lewin Frasier

Thomas Fuchs

What if we could obtain the memory, learning and perception benefits of “power naps” without actually sleeping?

A recent study in *Science* suggests that at least some of our primate cousins can. Researchers showed that brief naps (without rapid eye movement, or REM, sleep) improved macaques’ performance on a visual-perception task. The scientists then reproduced this boost by electrically stimulating the brains of awake monkeys in a way that mimicked sleeping brain activity—inducing a kind of “artificial nap.” The process, if effective in humans, might one day help boost cognition and treat sleep disorders.

The team first trained five monkeys on a task evaluating image orientations and tested them twice, with a 30-minute gap in which

they either had non-REM sleep or merely rested. The monkeys that slept performed significantly better on the second test. The researchers recorded thousands of neurons' activity in three brain regions: two visual areas and one associated with decision-making. In the monkeys that slept between tests, this activity was, oddly, less synchronized during the second task than the first.

"Sleep is a synchronizing phenomenon in which neurons go up and down together, but the level of synchrony after sleep is reduced compared with before," says the study's senior author, Valentin Dragoi, a systems neuroscientist at Rice University. "This is surprising." The size of this "desynchronizing" effect correlated with performance increases, suggesting that neurons firing more independently of one another may drive the improvement.

Low-frequency "delta" brain waves are known to be involved in memory maintenance. These waves dominated the monkeys' sleeping brain activity, and the team wondered whether they were behind the performance boost. To test it, the researchers conducted the experiment again—but instead of letting the monkeys sleep, they stimulated a visual brain region using a low-frequency electrical signal that mimicked delta waves. This stimulation also led to both reduced neural synchrony and better performance.

These findings imply that brain stimulation could deliver some of the benefits of naps without sleep. The results in primates strongly suggest "artificial nap" effects will translate to humans, says Sara Mednick, a neuroscientist at the University of California, Irvine, who studies the relation between napping and performance; evidence already exists that electrical stimulation during sleep can benefit humans' memory. "This work demonstrates that stimulating [when awake] at the delta frequency can mimic sleep benefits," Mednick says.

The researchers used electrodes placed in the monkeys' brains for stimulation, but they plan to test noninvasive techniques in people

with sleep disorders “in the near future,” Dragoi says. They also plan to study other senses, cognitive functions and brain regions, he adds. “Are different areas most effective for particular tasks? No one knows.”

Simon Makin is a freelance science journalist based in the U.K. His work has appeared in *New Scientist*, the *Economist*, *Scientific American* and *Nature*, among others. He covers the life sciences and specializes in neuroscience, psychology and mental health. Follow Makin on X (formerly Twitter) @SimonMakin

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https://www.scientificamerican.com/article/artificial-nap-could-provide-benefits-of-sleep-without-sleeping

Psychology

- **When a Nation Embraces a False Reality**
  A renowned psychiatrist and activist compares Trump’s election to other pivotal historical moments in which the ultimate victim was truth itself
- **The Hidden Costs of Men’s Social Isolation**
  When men suffer social isolation, women may pay the price, too

When a Nation Embraces a False Reality

A renowned psychiatrist and activist compares Trump's election to other pivotal historical moments in which the ultimate victim was truth itself

By Robert Jay Lifton

Rob Dobi/Getty Images

Daniel Patrick Moynihan, who was a New York U.S. senator for more than 20 years, once said, "Everyone is entitled to his own opinion but not to his own facts." That's a simple, profound and true statement.

Moynihan's words have particular relevance for our country and society after Donald Trump's victory in the 2024 presidential election. To put things directly, Trump was able to win because he and his followers convinced most of the country to believe in his falsification of factual truth.

Factual truth is distinct from ideology or bias or personal opinions of any kind. For example, the factual truth is that my name is Robert Jay Lifton, I am a research psychiatrist who studies the

psychological roots of war and political violence, and I am writing this essay for *Scientific American*. This sentence is declarative and makes an irrefutable point. That irrefutability is the source of the appeal of factual truth.

In contrast, when factual truth breaks down—with a denial, say, of the outcome of a legitimate election—a rush of falsehoods may inundate an entire society. That is because factual untruth requires continuous additional untruths to cover and sustain the original one. And the defense of continuous falsehoods relies on more than repetition; it requires intimidation and can readily lead to violence. Writer Philip Roth had both the falsehood and the violence in mind when he spoke, in his 1997 novel *American Pastoral*, of the "indigenous American berserk."

> It is wrong and misleading to speak of the U.S. as a "post-truth" society.

What results from this situation is "malignant normality," society's routinization of falsehood and destructive behavior. This shift can produce psychic numbing, the inability or disinclination to feel, which can reach the point of immobilization.

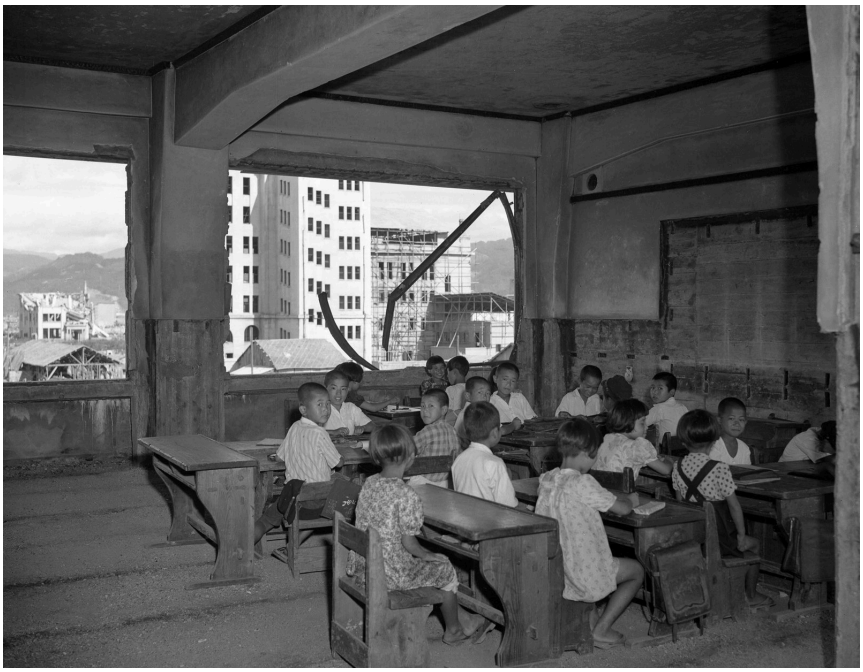
Malignant normality has much overlap with "sanewashing." That term connects with a wider audience but can become glib and vague. Malignant normality, in contrast, more strongly suggests a psychological experience on the part of individuals and groups.

Given how widespread falsehoods and lying have become, any reference to the value of truth-telling can seem counterintuitive. But factual truth-telling can bring psychological relief to the teller, who can then disengage from malignant falsehoods. In this way, truth-telling helps to diminish psychic numbing.

I have also emphasized in my work how much we human beings are meaning-hungry creatures. This idea is radically true for

survivors of war, nuclear or conventional, or other extreme trauma. For any such meaning to be convincing, it must be based in factual truth.

It is wrong and misleading to speak of the U.S. as a “post-truth” society. Rather we are continuously engaged in a struggle for truth-telling, which can be a profoundly difficult enterprise, as the 2024 U.S. elections made all too clear.



Children in Hiroshima one year after the bomb.
Bettmann Archive/Getty Images

To cope with the catastrophe of a second Trump administration and to counter the serial lying, we need to use every imaginable means of truth-telling. And the truth-telling itself becomes an expression of activist resistance.

In each of my research studies, I have sought to bear witness to the truths I have encountered. The principle of truth-telling has been central to all my work. In my 1967 book about Hiroshima, for instance, my work took the form of a scientific interview study of *hibakusha*, the survivors of the atomic bomb. But I found it necessary to add a broader ethical commitment to tell the story of the bomb’s annihilative human impact. I had to become a

witnessing professional, which meant not only revealing the full Hiroshima catastrophe but combating the nuclearism that led to it, the embrace of these weapons to solve human problems and the willingness to use them.

Truth was at the heart of my 1973 study of antiwar Vietnam veterans and their movement. The veterans I interviewed came to find their meaning of the war in its meaninglessness. Indeed, Vietnam Veterans Against the War (VVAW), a nonprofit advocacy group founded in 1967, affirmed that meaninglessness, as well as the veterans' committed effort to oppose their own war.

Hannah Arendt, a German American philosopher well known for her study of totalitarianism, noted in her 1971 essay "Lying in Politics" that it relies on "the organized lying of groups." She pointed out that Adolf Hitler and his propaganda minister Joseph Goebbels promoted what they themselves called the "big lie," not only to suppress people but to control their sense of reality. In that way, Nazi leaders could seek the ownership of reality by achieving widespread national belief in falsehoods. In a sense, all of Germany became a mystical cult, with Hitler its guru and savior. Truth-telling was also at the center of my 1986 study of the murderous behavior of Nazi doctors.

There are parallels to this cultlike aspect in Trump's claim to omniscience, believed by his hardcore followers, and his continuous claims on the ownership of reality.

Although they lost the election, Kamala Harris and Tim Walz touched a national nerve when they began using the word "weird" to describe Trump and his running mate, JD Vance. This was because it brought us collectively back to a democracy that functions on factual truth. A weird person is one you should never follow, because if you do, you take on some of that weirdness, the loss of reality and overall obliviousness to factual truth. That becomes very dangerous to a society facing planetary threats such

as nuclear war and global warming. Weirdness threatens our security, individually and nationally. But rather than avoidance, the election sustained and extended our dangerous participation in weirdness.

In sharp contrast to the serial falsehoods of Trump and Vance, the Harris-Walz team sought to uphold truth-telling throughout the election process and constantly called out those lies. To be sure, Harris and Walz did sometimes exaggerate claims, leave out uncomfortable changes that each underwent in their advocacy and avoid difficult topics. But they talked about factual matters and factual possibilities.

The election was an ultimate test of the amount of factual truth our society could manage. Not enough, it turned out. But even now our society still hungers for factual truths. Trumpists are likely to continue their creation of atrocity-producing situations, whether having to do with “ungoverning,” climate, threatened violence, or harmful policies around the lingering planetary threat of COVID. But we are not helpless before them.

In response to my study of Nazi doctors, some friends would ask me, “Now what do you think of your fellow human beings?” They were expecting me to say, “Not very much.” But my answer was that we could go either way. We could perish in the face of our catastrophes or survive them by making use of our “better angels” (in Abraham Lincoln’s words), which can give us sufficient survivor wisdom to keep our species going.

We are not condemned by a death drive to destroy ourselves, nor is it certain that we will sustain a truth-centered, life-enhancing ethos. But we have the capacity for that ethos, which provides a strong source of hope.

The award of the 2024 Nobel Peace Prize to *hibakusha* group Nihon Hidankyo for its antinuclear activism is a powerful assertion

of such hope. So was Harris's insistence that, although she conceded the election, she would never give up the struggle "for freedom, for opportunity, for fairness and the dignity of all people."

We cannot expect that we will eliminate falsehood entirely. There is no absolute moment of realized factual truth. Rather we are engaged in an ongoing struggle, as individuals and as a country, on behalf of the decency, necessity and satisfaction of truth-telling.

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

Robert Jay Lifton's works on psychology and history include his National Book Award winner *Death in Life: Survivors of Hiroshima* (Random House, 1967), *The Nazi Doctors: Medical Killing and the Psychology of Genocide* (Basic Books, 1986) and *Witness to an Extreme Century: A Memoir* (Free Press, 2014).

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https://www.scientificamerican.com/article/when-a-nation-embraces-a-false-reality

The Hidden Costs of Men's Social Isolation

When men suffer social isolation, women may pay the price, too

By Angelica Puzio Ferrara & Dylan Vergara edited by Daisy Yuhas

Christine Rösch

Men are struggling—at least, that's what many headlines suggest. Compared with women, men report having fewer and less supportive friendships. They lag behind dramatically in achievements such as higher education attainment. Suicide rates, too, reveal a grim gender disparity: women attempt suicide more often, but men are far more likely to die by it.

Concerns about these and other related issues have become a priority for some of the biggest philanthropic lenders on the planet. Although these challenges rightfully demand resources and attention, public discourse often stops short of discussing men's issues as interconnected with women's lives. If men are in trouble, what does that mean for women?

In our research, we explore a crucial puzzle piece in understanding men's broader struggles: the state of their close relationships. We

formed a theory about how the thinning fabric of many men's social worlds may place added strain on the women in their lives. Our work ties together several threads of evidence from psychology and sociology: men's struggles to build socially supportive networks, women's outsize role in sustaining men's social support systems, and inequality in the work men and women perform in their private lives.

Life in many Western nations has become more socially isolating for everyone in the past century. Men, however, are at the most risk of social isolation, especially in countries where people value individualism highly. Although this risk is greatest for older men, nearly two thirds of young American men report that "no one really knows me well." Nearly half of men in the U.K. say they cannot confide in their friends about problems. Large U.S. Census–representative surveys indicate that the number of people who say they have no close friends at all has grown over the past 30 years, and that increase is higher for men than for women.

> Initiatives such as Men's Circle and Beyond Equality are creating spaces where men can open up to one another rather than just to female friends or romantic partners.

In other words, men may lack friends on whom they can rely. But that's not the only dynamic at play. Sociologists have shown that men's social networks are more dependent on romantic relationships than those of women. More specifically, among couples in a heterosexual relationship, men lean on their romantic partner more than women do. Women are more likely to name friends or family members as their go-to sources of close emotional support.

Researchers have documented this pattern over decades, primarily in older white adults. But more recent evidence suggests the trend holds steady across diverse groups of straight men and women at various ages. The stakes become even clearer when romantic

partnerships end: men's social networks often shrink, whereas women's remain intact. It's a striking imbalance that suggests men's emotional infrastructure is often built on foundations that women maintain.

Not all men rely disproportionately on women for social support; some are at greater risk than others. Cultural beliefs about gender may be an important predictor of this difference. In the contemporary West, norms around manhood and masculinity have emphasized qualities such as emotional stoicism, the idea that "weaker" or "softer" emotions should be withheld at all costs, and hyperindependence, the notion that men don't need help from anyone, especially other men. In fact, psychologists have shown that men and boys who strongly endorse these ideas have worse mental and physical health—and that they are less likely to have close friendships.

But entrenched norms around masculinity may shape more than just how men relate to other men. Social scientists have documented how women take on the brunt of emotional and logistical work to maintain harmony within their families. For example, women, more so than men, may be the ones who remember birthdays, plan outings and check on family members' emotional well-being. In the 1980s sociologist Carolyn Rosenthal coined the term "kinkeeping" for this kind of labor. In a nod to that language, we call the labor that women specifically put into helping men with frayed social ties "mankeeping."

Our theory has several parts. In line with past research, we suspect that men who adhere to rigid masculine norms are most prone to this dynamic and that women frequently perform invisible labor by arranging and encouraging men's social interactions. But we also anticipate that mankeeping places a measurable burden on women's time and well-being.

There are some clues to that effect in past research. In a study of Canadian couples, the late American Canadian sociologist Barry Wellman found that women actively facilitated men's social interactions with other men and had less time for their own friendships as a result. More recently, psychologists have found that women suffer psychological distress, relationship dissatisfaction and reduced personal autonomy when they overemphasize their partner's needs. We believe the wager many women make in mankeeping is a calculated one. Even at women's personal cost, these behaviors may reduce the burden of men's isolation on families, relationships between women and men, and men themselves.

Future studies by us and others will put our theory of mankeeping to the test. Measuring this dynamic means answering questions such as: Where is mankeeping most prevalent—and what can that tell us about those communities? Are women who have unequal support in their relationships with men truly more burdened? Are women who have mutually supportive relationships with their male partners more satisfied?

Ultimately mankeeping deserves attention for two reasons. If the hard work women take on as men's social networks thin has a defined name, other researchers around the world can join us in assessing this phenomenon and its effects. And women, especially those who experience mankeeping, can be empowered with language that makes their emotional labor visible. Scholars and advocates are already spreading the work, proposing terms such as *cargamigas* and *marigarderie* for Spanish- and French-language contexts, respectively.

Naming forms of inequality is also a first step toward naming solutions. Initiatives such as Men's Circle and Beyond Equality are creating spaces where men can open up to one another rather than just to female friends or romantic partners and practice emotional vulnerability and mutual support. The goal is not to re-create

exclusionary “boys’ clubs” but to build networks that disrupt the patterns of male behavior that basically don’t serve anyone. No matter the remedy, addressing the inequality women face as a result of mankeeping requires challenging rigid masculine norms that leave so many men with impoverished social ties to begin with.

IF YOU NEED HELP

If you or someone you know is struggling or having thoughts of suicide, help is available. Call or text the 988 Suicide & Crisis Lifeline at 988, use the online Lifeline Chat or contact the Crisis Text Line by texting TALK to 741741.

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.*

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Robotics

- **This Robot Copies Life—By Decomposing**
  A new soft robotic arm and its controller break down naturally

This Robot Copies Life—By Decomposing

A new soft robotic arm and its controller break down naturally

By Saugat Bolakhe edited by Sarah Lewin Frasier

Thomas Fuchs

Picture a robot. What do you see? A rugged, steel-clad machine built to transcend living beings' organic fragility? Unfortunately, this very quality now threatens to drown the planet in extremely durable e-waste. What if, instead, our increasingly prevalent machines were designed to decay and disappear—like life does?

For a study in *Science Advances*, researchers crafted a robotic arm, and a joysticklike controller to operate it, from pork gelatin and plant cellulose—materials sturdy enough to function yet delicate enough to degrade in backyard compost. After testing, both origamilike structures disintegrated in soil within weeks.

Biodegradable robotics often falls under the umbrella of soft robotics, which draws inspiration from nature's more pliable creations. "The field originated from materials science and chemistry rather than conventional robots that come from

mechanical engineering," says materials scientist Florian Hartmann of the Max Planck Institute for Intelligent Systems in Stuttgart, Germany. But a lot of early soft robotics prototypes still relied on synthetic polymers that linger as pollution.

Pingdong Wei, a materials scientist working with natural polymers at Westlake University in Hangzhou, teamed up with his friend Zhuang Zhang, a robotics engineer now at Fudan University in Shanghai, to assemble robots for the new study. Wei had long been intrigued by robotics, Zhang recalls, and raised the idea of creating a robot himself. "That's when I thought, Why not use the materials he works with to build one?"

They started with cellulose layers derived from cotton pulp, then added glycerol for flexibility and dried the layers for strength. "Cellulose is also cheap and easy to assemble," Wei says. To build sensors, the researchers used a conductive gelatin extracted from pork, in which the flow of ions changes when the material is stretched, bent or pressed. They then folded the flat films and sensors into 3D structures.

Wei and Zhang found that the controller and robotic arm stood up to both heavy use and a week of inactivity. Finally, they buried them both in a 20-centimeter-deep hole near their campus. Within eight weeks the machines were almost entirely gone.

"The way the researchers were able to engineer something so rigid yet so soft is impressive," says robotics engineer Ellen Rumley, who is also at the Max Planck Institute for Intelligent Systems. Neither Rumley nor Hartmann was involved in the study.

Wei and Zhang envision bots like these handling hazardous waste and then dissolving; they also propose robots that aid surgeries and then safely break down inside the body. But it's important to note that the technology is in very early stages.

“If we truly want to have a sustainable robot that goes outside in nature,” Hartmann says, “we also need to think of electronics or power supplies, or even batteries, that are biodegradable.”

Saugat Bolakhe is a freelance science journalist. He studied zoology as an undergraduate in Nepal and received a master’s degree from the Craig Newmark Graduate School of Journalism at the City University of New York. His work has appeared in *Scientific American*, *Nature*, *New Scientist*, *Quanta*, *Eos*, *Discover*, *Knowable* and other publications.

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| Section menu | Main menu |