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Lost Roads of the Roman Empire

The Scariest Problem in Math

The QUANTUM Revolution

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FEATURES

ON THE COVER
In a special report, we explore how computers that exploit the bizarre rules of the quantum realm could change the world. We investigate where the technology stands, what needs to happen for it to fulfill its promise, and which problems a truly useful quantum computer could solve.

Illustration by Violet Frances

Illustration by DTAN Studio

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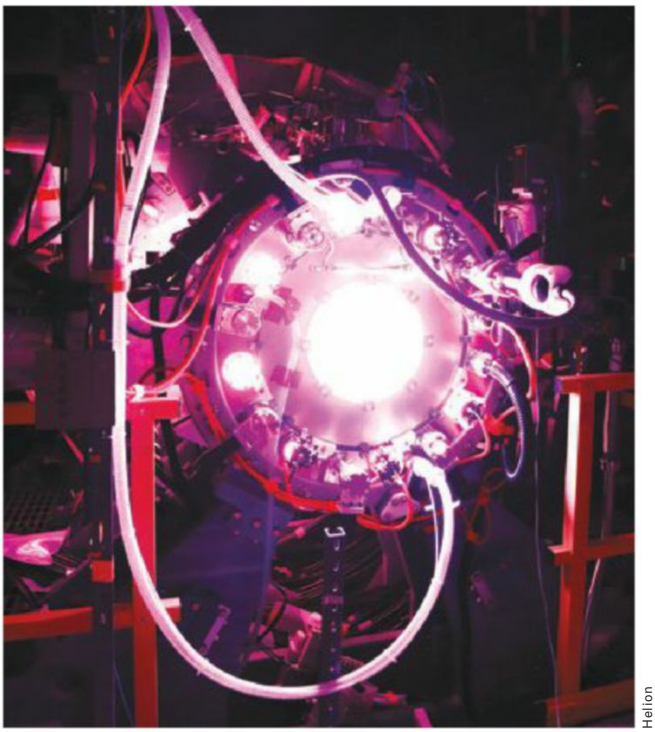

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A Real Quantum Leap

ONE OF THE ENDEMIC ILLNESSES of the American tech industry is an addiction to unsupported superlatives: Descriptors like "revolutionary," "game-changing" or "disruptive" are applied to inventions that are at best incremental and at worst of no use at all.

Despite the fact that I know this to be true, I now offer the following extraordinary statements: Quantum computing could change the world. It's transformative, monumental, unprecedented. A once-in-a-generation technology that shifts paradigms and ushers in a new era of innovation. A quantum leap, even.

Here's one example why: Modern finance—our entire economic system, really—relies on public-key cryptosystems that are essentially unbreakable. Even the consumer-level codes that encrypt your online banking are so hard to break that every computer on the planet working together would need longer than the age of the universe to brute-force them apart.

A quantum computer could factor those integers and steal your mortgage payment in just a couple of hours.

Of course, there's a catch, and it's a big one. Despite huge advances in the field, we don't actually know how to build a functionally useful quantum computer or even if such a thing is possible at all. In this month's cover story (*page 26*), science journalist and astrophysicist Adam Becker takes us inside the cryogenically chilled heart of quantum computing to find an answer: Will quantum computers transform medicine, materials science and cybersecurity, or is the tech industry betting billions on a sci-fi fantasy?

Elsewhere in the issue, *Scientific American* staff reporter Joseph Howlett seeks answers to another as yet unsolved problem that could reshape everything from cryptography to physics: the Riemann hypothesis, a 167-year-old conjecture so difficult to prove that top mathematicians avoid even trying. "The Scariest Problem in Math" (*page 52*) has a million-dollar reward for its solution, but Howlett explains why hardly anyone is trying to find it.

We also take time to reflect on a recently completed achievement that has impressed and inspired us all. Over 11 days in April, the Artemis II moon mission took humans back to the moon and farther from Earth than they had ever been before.

Journalist Nadia Drake explains how the triumphant expedition marks a new era of lunar exploration (*page 58*), while our own Joe Howlett explains why Artemis's future will be a game changer for astronomy (*page 66*). In "A Nuclear Moon" (*page 70*), volcanologist and science writer Robin George Andrews digs into why NASA wants to build a fission reactor on the lunar surface within the next five years and why that plan isn't as crazy as it sounds.

Finally, after all that looking forward to the future, we invite you to take a nice stroll down the roads of our ancient past. Archaeologist Tom Brughmans takes readers on a journey through a digital mapping project that is transforming what we know about the Roman Empire by combining centuries-old archaeological records with satellite imagery and modern topographic data (*page 42*). Brughmans and his team have assembled the first high-resolution digital map of Roman roads that shows the network might have stretched some 300,000 kilometers, carrying troops, grain, ideas and disease across an area rivaling the modern European Union.

So, yes, superlatives like "revolutionary" and "game-changing" do get thrown around too easily. But as this issue shows, science can make our world turn upside down, whether because of a qubit, a conjecture, a moonshot or a map of 2,000-year-old roads. Hyperbole isn't always hype; sometimes the truth catches up. ●

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

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LUNAR TIME CAPSULE

I excavated Peter Brannen's article "Can a Time Capsule Outlast Geology?" from a long-term storage site—my nightstand—where it had been protected by the superstratum of his book *The Story of CO_2 Is the Story of Everything.*

We have the capability to place a time capsule on or just below the surface of the moon. Calculations predict that our nearest celestial neighbor will not escape Earth's orbit prior to when it is engulfed by the expected red giant phase of our sun some five billion years hence. I would therefore suggest we deposit the long-term records we wish a future civilization and/or species to use to evaluate our rather mixed legacy near a lunar pole. Alternatively, I might consider offering my nightstand.

DANIEL SPITZER *PIERMONT, N.Y.*

END REFLECTION?

The dangers of creating a bacterium with mirror molecules are clearly expounded by Vaughn S. Cooper in "Deadly Mirror." But the article doesn't mention the danger of encountering mirror DNA while exploring outside our planet. I would think the chances of encountering such DNA as part of an extraterrestrial lifeform would be higher beyond the moon and Mars—and would be much greater as we explored more of our solar system, including bodies that come from other solar systems.

ED YALOW *VIA E-MAIL*

I found Cooper's article oddly comforting. I've been feeling bad about the fact that, within several thousands of years, inevitable periods of societal instability will cause improper nuclear waste storage somewhere on the planet, and we will be responsible for the suffering of innocent future humans and animals when they are unsuspectingly exposed to dangerous levels of radiation that will make them sick.

I don't think I have to worry about that anymore: a mirror bacterium will be created by somebody in a dark lab using some kind of AI-powered chemical printer before that happens. We will be wiped out pretty quickly, and multicellular life will evolve again to become compatible with the existence of both threats—and, let's hope, a little less "intelligent" this time.

FRANCES SIMONSON
REGINA, SASKATCHEWAN

SEEING DISTANT STARS

In "The First Stars," by José María Diego Rodríguez, the ability to see very distant stars via the use of gravitational lensing by large galaxy clusters is nicely described and mentioned as a means of possibly further understanding dark matter. Is what allows for the estimate of dark matter within a cluster the geometric arrangement of the situation, the focal lengths and, especially, the amount of light bending associated with the very small regions called caustics? Or are there other factors involved?

G. RICHARD THOMPSON *VIA E-MAIL*

DIEGO RODRÍGUEZ REPLIES: *The driving factor is the amount of curvature that can be produced by certain dark matter models that can result in small lenses (microlenses). The microlenses can be seen best near cluster caustics. Some models are able to produce additional microlenses, whereas other models don't. The distant stars can be used to create a census of microlenses that favor some dark matter models and discard others.*

THE MANY MOODS OF PARENTING

"The Neuroscience of the 'Parenting Paradox,'" by Anthony Vaccaro [Mind Matters], describes the author's research around a seeming contradiction: "parents report lower mood and more stress and depression in their daily lives than adults without children"; at the same time "parents also tend to report greater life satisfaction in general." The article presents the idea as if parents are less happy day to day but more fulfilled overall. But I don't think this is really a paradox—it's about how happiness is measured. Quick daily mood check-ins mostly capture stress and exhaustion while missing the small joys, pride and love woven throughout parenting. Raising kids can be tiring and meaningful at the same time. Much of the stress parents feel also comes from lack of sleep, financial pressure or limited support—not simply from having children.

JAMAL I. BITTAR *TOLEDO, OHIO*

CONSCIOUSNESS VS. AWARENESS

When I began life as a neuroscientist 40 years ago, the nature of consciousness was understood about as well as it is now. In "The Hardest Problem," Allison Parshall uses the terms "consciousness," "awareness" and "conscious awareness" interchangeably. It might be to our advantage to look at consciousness and awareness as different things.

Admittedly, without the benefit

"I would suggest we deposit the long-term records we wish a future civilization to use to evaluate our rather mixed legacy near a lunar pole."
—DANIEL SPITZER *PIERMONT, N.Y.*

of functional magnetic resonance imaging (fMRI) and other modern techniques, thinkers such as Dōgen, Hongzhi Zhengjue, and many others of the long Buddhist tradition reasoned that consciousness is impermanent, mutable, divisible and easily misidentifiable as the "self" but is emergent from and dependent on awareness, a fundamental and unchanging thing. This may point to a distinction that could be usable by scientists.

KENNETH B. THOMAS *VIA E-MAIL*

SPACE ROCKS

In "Inside Asteroid Family Trees" [The Universe; January], Phil Plait writes that when two space rocks collide in the main asteroid belt, "their high orbital speeds mean they can have collision velocities far higher than that of a rifle bullet." I'm puzzled by this comment. I assume that because the two asteroids are in the same orbit, they have the same speed, so their relative speeds would be very low. Where would the collision's high velocity come from?

ROBERT I. MASTA *ANN ARBOR, MICH.*

PLAIT REPLIES: *While it's true that most asteroids orbit in the same direction around the sun—counterclockwise if you're looking "down" on the solar system from the north—the orbits are all different shapes. An asteroid that's on a more elliptical orbit, for example, may be moving significantly faster when it's closest to the sun than another asteroid that's on a nearly circular orbit at that same distance. Also, some asteroids have their orbits changed by Jupiter's gravity, which can alter their velocities. Collisions in the asteroid belt may be less energetic on average than when an asteroid hits Earth, but they can still disrupt a largish rock to create families with many members.*

ERRATUM

"War's New Fuel," by Sarah Scoles [The Science of War; April], incorrectly identified the image of a water-filled structure as a cooling pool. It is the open core of a nuclear reactor.

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ADVANCES

PLANETARY SCIENCE

Weird Worlds

This sulfurous hell world might change the way we classify exoplanets

TRILLIONS OF MILES FROM EARTH, a cluster of planets whirl around a sun of their own—and one of the worlds is a sulfur-swathed oddball. Research suggests the planet, L 98-59 d, would smell like rotten eggs and is covered in a mushy magma ocean. And it isn't just an outlier in its home solar system. So far it's the first exoplanet found to fit this peculiar description, and it seems to be defining a category of its own.

Scientists first observed the planet in 2019, when the Transiting Exoplanet Survey Satellite caught a glimpse of L 98-59 d passing in front of the red dwarf star at the center of its system. Afterward, observations from the Hubble and James Webb Space Telescopes hinted at the planet's composition, but the more scientists learned, the less this newfound orb seemed to fit into existing categories for planets of its size. Neither rocky with a thick hydrogen atmosphere nor an ocean world, L 98-59 d might occupy a new class of molten, sulfurous exoplanet, according to a study in *Nature Astronomy*.

"It's pretty hellish, it's pretty alien," says Harrison Nicholls, lead author of the study and a postdoctoral researcher at the University of Cambridge. "With more data, we might find that there are other planets like it, too."

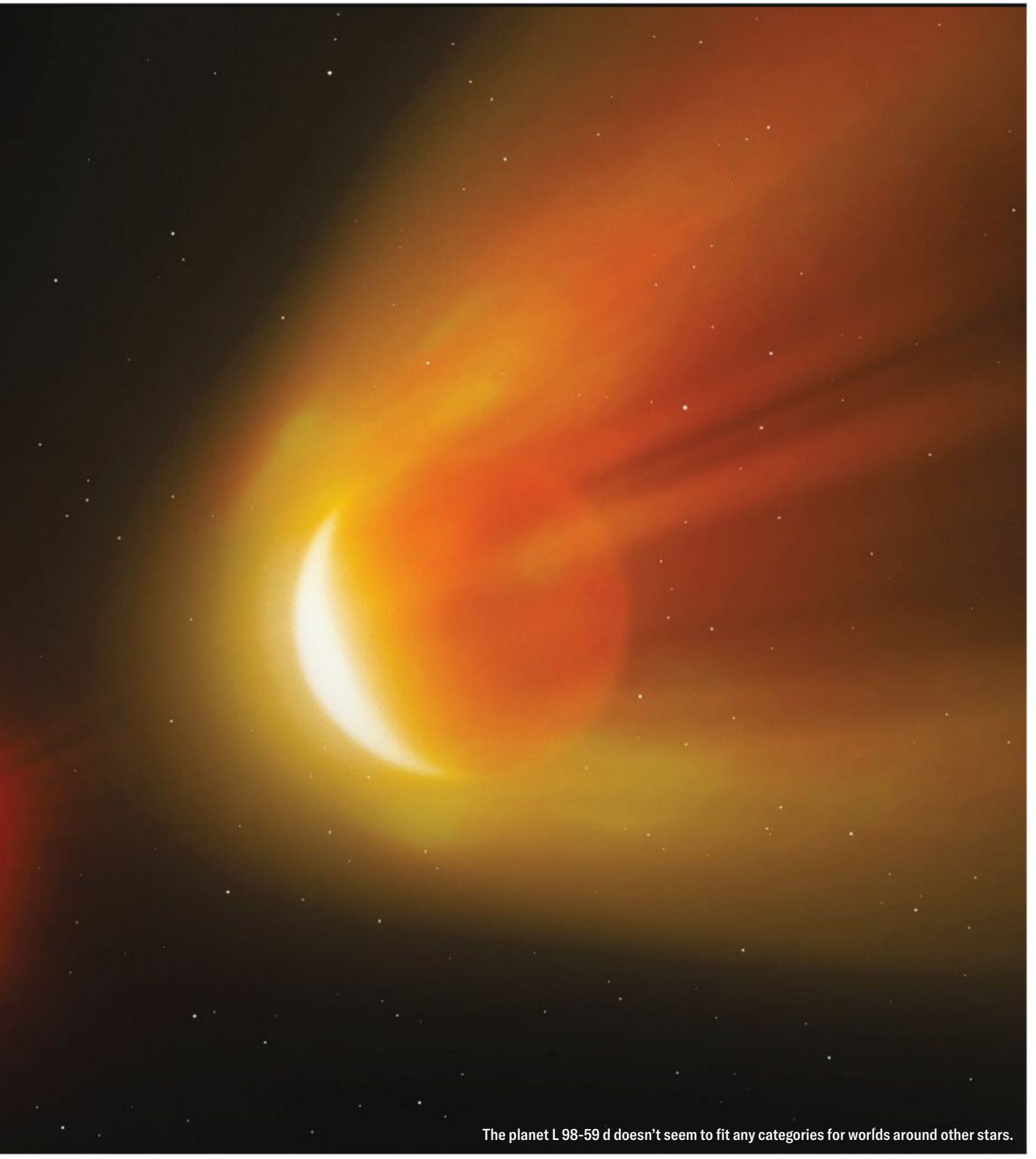
The first confirmed detection of an exoplanet, though long anticipated, was only 34 years ago. Increasingly powerful telescopes have since launched the field forward with more detections—now more than 6,000 in total. But it's one thing to find an exoplanet and quite another to understand its surface conditions.

Astronomers can gauge the size and mass of far-flung worlds by watching how light dims and wobbles as the planets cross in front of their home stars. They study planets' composition by measuring the light that passes through their foreign atmospheres. Theorists then bring these wide-ranging worlds to life through cohesive models of the planets' features and formation. "Even with perfect data, the numbers don't tell you anything on their own," Nicholls says. "And we're limited a little bit by what we can be certain about" with planet L 98-59 d.

Scientists know that the planet is about five billion years old and that its searing surface temperature reaches more than 1,500 degrees Celsius. It's about 1.6 times the size of Earth, but it has an unusually low density. The strangest feature in the data, however, is its sulfur-rich atmosphere. Many young planets, including early Earth, have a brief "rotten eggs phase" because of intense volcanic activity. But the hydrogen sulfide and sulfur dioxide produced in that period don't usually stick around for five billion years.

Researchers used computer models to turn back the clock on L 98-59 d and figure out how it could have formed. They found that a disk of material around a star with enough of these volatile components could create a type of planet that's molten from its sticky surface all the way to its core—and that such planets might be common.

"In general, in science we start by telling very simple stories, and those stories get more elaborate as time goes on [because] we have to explain a wider



The planet L 98-59 d doesn’t seem to fit any categories for worlds around other stars.

Illustration by Mark Garlick

range of things or more detailed measurements," says Heather Knutson, a planetary scientist at the California Institute of Technology, who was not involved in the new study. "This is a great example of that."

Because the field of exoplanet research is so new, there are not yet enough categories to adequately describe the diversity of these bodies. L 98-59 d is a step toward "moving beyond boxes" of discrete planet types—such as ocean or rocky worlds—and establishing a continuum of types that might give insights into how worlds change and evolve, says Julien de Wit, a planetary scientist at the Massachusetts Institute of Technology, who also was not involved in the study.

"Really, the dream of an observer is to construct a classification scheme that then doesn't just describe the universe; it tells you something new about the universe," agrees Thomas Beatty, an astronomer at the University of Wisconsin–Madison, who was not part of the study.

Perhaps the best example of such a classification system, Beatty says, is the Hertzsprung-Russell diagram. This scatterplot of stars illuminated the process of stellar evolution and jump-started the field of stellar physics more than a century ago. That work started with simply observing individual stars and sorting them into categories—just like scientists finally have the technology to do with exoplanets today. Some hope that an exoplanet-classification system will similarly help

BIOLOGY

Tiny Climbers

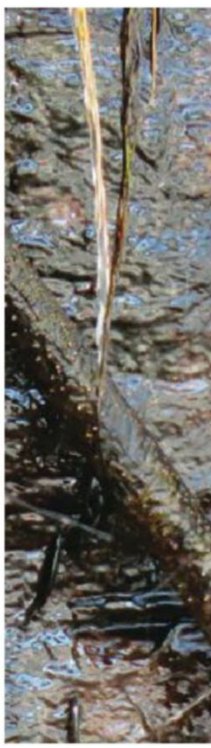
Ziti-size fish scale a massive waterfall

THE WORLD CHEERED when Alex Honnold free-climbed a 101-story skyscraper in Taipei. Gather now, fickle public, to applaud the *new* free-climbing champion: the shellear, a fish that is about the size of a ziti noodle—and that can scale a 50-foot waterfall.

During major floods, thousands of the tiny fish convene at Luvilombo Falls in the upper Congo River Basin to undertake a peculiar vertical migration, described for the first time in *Scientific Reports*.

At sunset they sidle up to the splash zone—the damp areas on either side of the waterfall's main flow—and press their fins flat against the sheer rock face. The fins are covered in what study lead author Kiwele Mutambala Pacifique, a Ph.D. student at the University of Lubumbashi in the Democratic Republic of the Congo, calls *petit crochet* (French for "little hooks"). These microscopic single-celled structures give the shellear its grip, he explains.

Then, with a wiggle of the tail, "it's as if the fish is swimming but in vertical," he says. "It's beyond imagination."



Kiwele Mutambala Pacifique

How can such a little fish scale a vertical distance that is, proportionally to its size, 50 percent taller than Honnold's skyscraper? In this case, by taking a lot of breaks. The shellear travel with bursts of upward motion that are peppered with short rests under a minute long and longer breaks of about an hour—whenever they reach a ledge where they can lay their fishy head. The entire journey takes about 10 hours, and "most of that is, in fact, resting time," says Emmanuel Vreven, an ichthyologist at the Royal Museum for Central Africa in Belgium and a co-author of the new paper. "Some of the fish fall down during climbing and have to start over again."

Clearly, the shellear are highly motivated to climb; whether the journey helps the fish evade predators at the foot of the waterfall or pursue a mate or a meal upstream, scientists aren't certain.

It's "fabulous" to see a fish use "friction enhancers" like these hooks to cling and climb, says Adam Summers, a biol-

to resolve the unknowns in planetary evolution, such as how the process differs among planet types.

Although studying weird worlds such as L 98-59 d will probably help to clarify how planets evolve, researchers are still working to understand this particular one. A molten magma world best fits the data collected so far, but scientists are observing the exoplanet to eliminate uncertainties—such as how much sulfur is in its atmosphere—that could pin down our understanding of what things are like on the surface of L 98-59 d.

Researchers suggest that we should have an even clearer conception of the planet after another year or two of observation. By then L 98-59 d may not be alone in its proposed new class. "The field is moving so quickly, and we're learning there's so much we don't know," Nicholls says. "I do think that we have good reason to believe that the sulfur world is probably going to be quite a substantial category of planets."

—K. R. Callaway

The 50-foot Luvilombo Falls provides the ultimate climbing challenge to tiny fish called shellear.

ogist at the University of Washington, who studies unusual adaptations in fish and wasn't involved in the study. Other species, such as lumpsuckers—Summers's longtime favorite—employ suction to stick to rocks. (In fact, an April 1913 issue of *Scientific American* includes an article about a South American catfish that used suction in a similar way.) But the friction trick most likely works for shellear only because of their diminutive size—indeed, the authors noticed that larger individuals get left behind at Luvilombo.

The researchers hope the shellear's athleticism will inspire ecotourism for African fauna. Safari-goers are too often preoccupied with the "Big Five" game animals—lions, leopards, rhinoceroses, elephants and buffalo. "But there are amazing things to see in little fish," Vreven says. *—Elizabeth Anne Brown*

MATH

Fractal Geography

Scientists catalog the "fractalness" of more than 130,000 islands

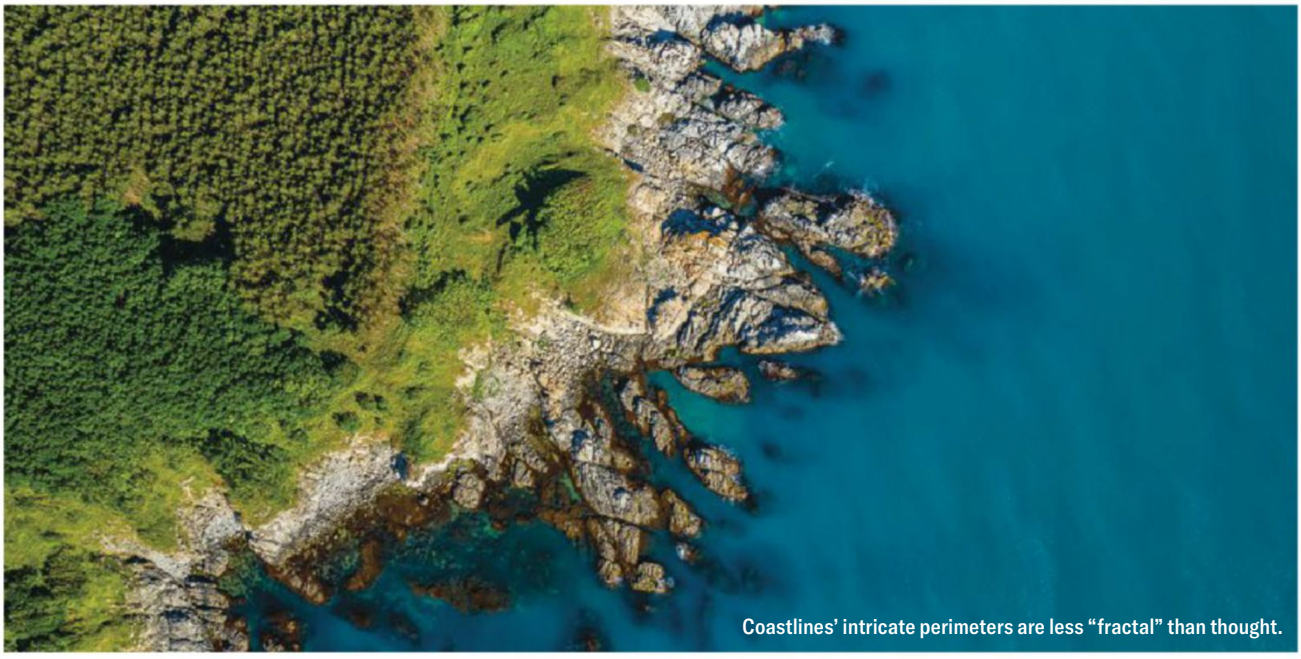
IN 1967 MATHEMATICIAN Benoit Mandelbrot observed that the coastline of Great Britain is impossible to measure—its perimeter gets longer the more closely you measure it. At that point he was eight years away from coining the term "fractal": a shape containing smaller parts similar in shape to the larger whole that become apparent as you zoom in, creating an infinite, and infinitely complex, repeated pattern. Now the so-called coastline paradox he observed is one of many known examples of fractals in Earth's geography. But recent work has found that coastlines may actually be far less fractal than thought.

The research, published on the preprint server arXiv.org and accepted in *Geophysical Research Letters,* stitches together geographic data for more than 130,000 of Earth's islands to show that although the landmasses behave like fractals in certain respects, the extent to which they do—their fractal dimension—differs depending on what geometric feature of the island you're looking at. Coastlines, researchers found, come in last (after, for instance, surface elevation). This discovery is a departure from current fractal models of Earth's surface, according to University of Chicago mathematician Matthew Oline, the study's lead author.

A shape's fractal dimension tells you how much you can zoom in to keep the fractal pattern repeating. An island coastline with a low fractal dimension might look almost completely smooth, whereas one with a high fractal dimension will have a visibly bumpy, complex border even as you zoom in further. This concept extends to other geometric features of islands, including size distribution, elevation and volume. For example, small islands are far more abundant than large ones—a pattern of complexity that makes the distribution of sizes for Earth's islands fractal, too. In typical models of Earth's surface, all features scale with the same fractal dimension.

Oline found, however, that some island features can handle more zooming in than others on their fractal detail. He says this result isn't remarkable, because existing fractal models are more like "toy models" than an exact representation of Earth. What was unexpected, though, was the stark difference between the different geometric features' fractal dimensions—especially for the surprisingly smooth coastlines. "The coastline paradox is the one people have heard of, but actually, the coastlines are the smoothest feature we see here," Oline says. This finding aligns with the idea that factors such as sedimentation and erosion would chip away at a coastline's complexity more than, say, a mountaintop's.

Andreas Baas, a geomorphologist at King's College London who was not involved with the work, was also surprised by how smooth coastlines are compared with previous studies' estimates. He says the authors' approach to calculating the fractal dimensions was "very rigorous," but he is more cautious about attaching meaning to the differences. Their hypothesis opens up "new avenues for research" to close existing gaps between studies involving coastline and surface models, Baas says. "It would be interesting to combine these models to see whether they can reproduce observed [fractal] relationships." —*Alex Music*



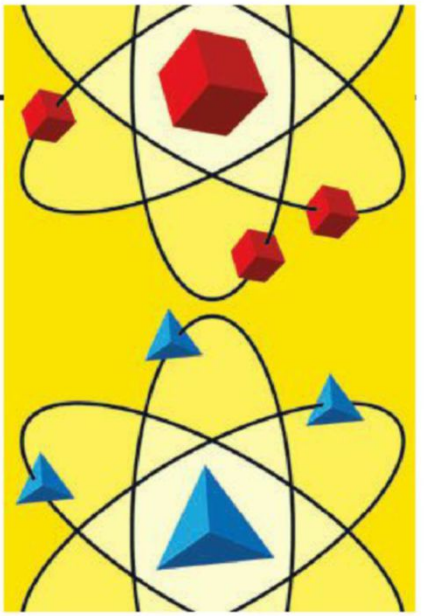
Coastlines' intricate perimeters are less "fractal" than thought.

jk78/Getty Images

PHYSICS

Atomic Snowflakes

Could each atom in the universe be unique?



ONE OF PHYSICISTS' FOUNDATIONAL assumptions is that atoms aren't unique—if two atoms have the same number of protons, neutrons and electrons, they will look and act exactly alike. This belief is fundamental to our understanding of physics and matter in the universe, and it paves the way for fields that rely on predictability, such as quantum computing. Atoms' indistinguishability is still just an assumption, however, and scientists have a plan to put it to the test.

In a recent paper published in *Physics Letters B*, physicist Mark Raizen of the University of Texas at Austin proposes a series of experiments to coax out potential differences from these seemingly identical particles for the first time.

"We like to have theory and experiment march together," Raizen says. "This question has never been tested experimentally before, so that's what, to me, makes it interesting."

If atoms were distinguishable, looking at two atoms of the same type would be like looking at two cars of the same make and model, says Christian Sanner, a physicist at Colorado State University, who was not involved in the new paper. Straight off the assembly line, they might seem impossible to tell apart. But if you move closer to precisely measure the tightness of the bolts and the tiny gaps between the doors and the frame, slight differences will become more apparent.

To get extremely precise atomic measurements, Raizen proposes an experiment using a laser to cool and trap individual isotopes—variants of atoms—in an extremely precise atomic clock. This setup would let researchers detect minute differences in the isotopes' energy levels by examining nuances in the magnetic field created by each particle's spinning nucleus, called the nuclear magnetic moment.

The experiment builds on several decades of Raizen's previous work. Starting when he was a postdoctoral fellow at the National Institute of Standards and Technology, he helped to develop a way for atomic clocks to cool down and trap a series of charged atoms "like pearls on a necklace." Some of his later work focused on creating methods of controlling these trapped particles. This research led to more efficient ways of separating isotopes, an important step in many radiation-based cancer treatments and diagnostic imaging—and a key part of his plan to test for distinguishability.

"It does close a circle that started for me 30 or 35 years ago, and in that regard, it's very gratifying and exciting to be able to combine these things which I never anticipated going back to," Raizen says.

Even scientists who aren't fully convinced that atoms could be unique agree that experiments testing widely accepted assumptions are an essential part of the scientific process and the long history of innovations driving the field. "That's the attitude of modern science," Sanner says. "Speculation is what is needed to come up with new, creative ideas, but in the end, we consider experimental results as the actual decision-maker." —*K. R. Callaway*

Illustration by Thomas Fuchs

GEOLOGY

Early Plates

Scientists found the oldest direct evidence for Earth's tectonic motion

THE COLOSSAL MOVEMENTS of tectonic plates shape our world, influencing the composition of Earth's atmosphere, the planet's protective magnetic field and perhaps even the flourishing of life. Now researchers have compelling evidence that some form of plate tectonics might have started as early as 3.48 billion years ago, according to a study in *Science*.

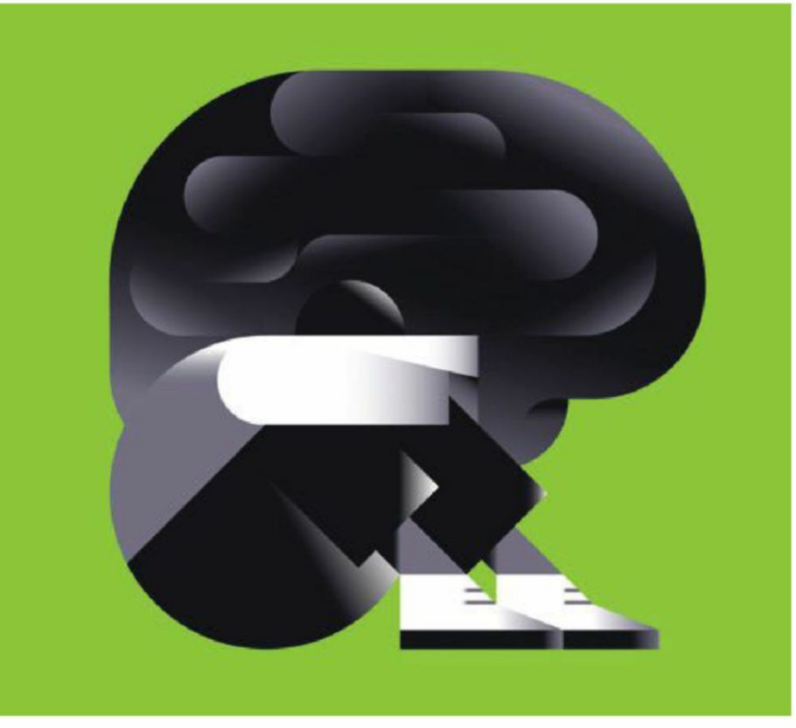
Using magnetic traces from ancient pieces of Earth's crust, researchers found that a chunk of what is now Western Australia drifted toward the magnetic north pole over a few million years as part of South Africa remained stationary. It's the earliest documented instance of relative plate motion by more than half a billion years, and it has implications for understanding early life on Earth and how the planet's tectonic activity began. [*Disclosure: The author of this article embedded with the research team during last year's field season.*]

Earth today is a jigsaw of giant chunks of crust that travel across the planet, smashing together like huge bumper cars, pushing up mountain ranges and melting back into magma along their edges. All this activity, called plate tectonics, seems to be unique in our solar system. It's believed that our rocky neighbor planets instead have a continuous, solid shell.

No one knows, however, how or when plate tectonics got started on Earth in the first place. "It's one of the most fundamental questions in Earth science," says study co-author Roger Fu, a Harvard University paleomagnetist. Geologists use various tools to investigate the state of Earth's crust over the eons, but the gold standard is evidence of relative motion: one piece of Earth's crust moving away from or toward another piece. For that, Earth's magnetic field—powered by the motion of the planet's core—holds the key.

Like any magnet, Earth has north and south magnetic poles, aligning roughly with the globe's geographic poles. These poles flip at irregular intervals; the last such reversal happened about 780,000 years ago. (Right now Earth's magnetic north is technically in the Southern Hemisphere.) The direction and angle of lines of force curving between the poles become imprinted in molten rock as it solidifies near the planet's surface, providing clues to where ancient rocks have been.

To find such traces, the team analyzed rock samples from remote parts of Western Australia and South Africa. These regions contain some of the planet's oldest cratons, chunks of now stable crust that have survived billions of years of grinding and melting processes and that form the building blocks of continents. The rock layers' magnetic record shows the shifting of a chunk of the craton in Australia while part of the craton in South Africa stayed still. Such motion is exciting because it "suggests there's likely to be a plate boundary between the two [cratons]," says Michael Brown, a University of Maryland emeritus geologist, who was not involved in the study.



PSYCHOLOGY

Challenging Measures

Depression questionnaires may not work the same for highly intelligent people

PSYCHOLOGISTS HAVE FOUND that two common questionnaires for assessing depression don't work for comparing people of differing intelligence—and the problem may extend to other conditions and traits.

For a recent study in the journal *Intelligence*, Stanisław Czerwiński of the University of Gdańsk in Poland and his colleagues investigated how intelligence correlates with mental health. They hypothesized that the association between intelligence and better mental health starts out positive as it approaches the high end of the IQ scale, then turns negative.

The researchers analyzed data from two U.S. surveys that tracked thousands of people over decades. To estimate IQ, these surveys used an aptitude test that measures math and

Illustration by Chiara Morra

Multiple researchers agreed that this study's findings likely represent the earliest we will be able to see such results, as so few rocks remain intact from Earth's first billion years. "It's like having a 1,000-piece jigsaw, but you have only 35 pieces," Brown says. The relative motion doesn't tell us exactly what was going on in this period, he adds, but it can put new limits on the mathematical models that researchers use to re-create ancient Earth.

Besides the evidence of relative tectonic motion, Fu and his colleagues also found evidence of the earliest known reversal of Earth's magnetic poles, around 3.46 billion years ago. Together, the study's findings "demonstrate that Earth was behaving very similarly" to what we see today, according to Jun Korenaga, a Yale University geophysicist, who was not involved in the study.

The Western Australian craton the team studied is home to the oldest confirmed structures left behind by single-celled organisms, which date back roughly 3.48 billion years. Knowing the latitude of those rocks at the time could help researchers learn more about the conditions where early life flourished. And understanding what kind of tectonics operated back then may set limits on how Earth's modern plate tectonics got started. If we know what Earth's early tectonics looked like, we can start to hunt for similar behavior on other planets, too.

"What kind of planet did life first appear on?" Fu wonders. The answer, he says, "has implications for how abundant life is likely to be in the universe." *—Marissa Grunes*

Alec Brenner/Harvard University/Yale University

Outcrop of a 3.5-billion-year-old "pillow basalt" lava flow

language abilities. Each used a different well-established mental health scale containing questions about things such as mood, sleep and appetite.

The data revealed the curved relation the researchers were expecting: the highest intelligence levels seemed to be associated with declines in mental health. But then the scientists found a problem. To make sure their results were valid, they ran statistics tests to determine whether the mental health measures work the same for people at different intelligence levels, in part by calculating whether responses to individual questions reflect depression to the same extent for everybody. Both scales failed this test, meaning they can't be used to compare people with differing intelligence—and conclusions like this study's can't be trusted.

The finding casts doubt on previous studies that used these tools without accounting for intelligence and suggests depression screening in doctor's offices may be flawed. "Imagine we're measuring height, but our ruler is made of Silly Putty, so the length changes," says Nicole Beaulieu Perez, a psychiatric nurse at New York University not involved in the research, who studies disparities in mental health care and depression assessment. "How can we know how tall these people are?"

The study doesn't show what causes this effect, but in hindsight, Czerwiński isn't surprised. The questionnaires require a lot of interpretation of questions and answers, he says: "Very intelligent people may think about mental health differently and maybe experience symptoms differently."

To better assess depression in groups of people with varying intelligence or to compare groups that might differ in intelligence, researchers will need better tools. Researchers say new approaches could include digitally tracking sleep and other activities or "experience sampling," in which study participants are asked how they're feeling at random intervals rather than offering interpretations after the fact.

In a separate study, Perez recently found that evidence showing that depression scales hold steady across other features, such as gender and culture, is inadequate. "Depression is one of the most measured constructs in science, but we have this measurement problem," she says.

The study analyzed only two mental health scales, but Czerwiński says the problem is probably widespread wherever depression scales are used. The researchers are currently testing the evaluation of other psychological variables as well—they've seen similar results for loneliness, Czerwiński says, and they're exploring personality measures.

—Simon Makin

ANIMAL BEHAVIOR

Mating Arm

Reproduction in octopuses is even weirder than you think

OCTOPUS SEX HINGES on a bizarre anatomical trick. In lieu of a penis, the male has a special mating arm called a hectocotylus. He feels around with it inside the female's mantle—a bulbous structure behind the eyes that houses all of an octopus's organs, including reproductive ones—until he finds her ovary. He then slides a sac of sperm down his arm and deposits it. But the male can't actually see what he's doing. So how does he know when he's found the right spot to send in the sperm? The answer, it turns out, lies in the arm itself.

In a study published in *Science*, researchers show that the male California two-spot octopus's mating arm can sense sex hormones emanating from the female's oviduct, the passage to the ovary.

Chemotactile receptors in octopus arm suckers let the arms "taste" their surroundings through touch. But octopuses typically don't use the hectocotylus in hunting or seafloor exploration; instead males hold it close to their body when they're not mating. Nevertheless, this appendage, like the octopus's other seven, comes loaded with receptors, says Harvard University molecular biologist Pablo Villar, co-lead author of the paper.

California two-spot octopus

Windzepher/Getty Images

To understand the purpose of these receptors, Villar and his colleagues coaxed a pair of California two-spot octopuses to mate in the laboratory. Because octopuses can be aggressive, the researchers installed a divider in the tank with a few small holes so the pair could warm up to each other. This arrangement might seem ill-suited for lovemaking, but surprisingly, the male simply reached across the barrier and got busy. The investigators tested four more mating pairs and got the same result—even in total darkness. "They made it seem super, super natural," Villar says.

Octopuses are highly visual creatures that communicate through body language and color changes. But these flourishes don't seem essential for mating. "They were able to do it with no visual cues," Villar says, "just by touching." Female octopuses, he and his team theorized, must release some kind of chemical signal to guide males in.

They found that the octopus oviduct produces enzymes that are used to make the sex hormone progesterone. This hormone seems to attract the hectocotylus: when the researchers attached tubes to the holes in the tank divider, each coated with a different chemical, males were quickly drawn to the one containing progesterone. Even amputated mating arms responded to progesterone but not to other molecules.

Many animals rely to some extent on the detection of sex hormones for mating. But the organ that senses those hormones is usually separate from the one that delivers the sperm; in male octopuses, the hectocotylus does both. That way, says molecular biologist Nicholas Bellono, a co-author of the study and Villar's postdoctoral adviser at Har-

vard, "you make sure at the site of release that that's the exact spot."

Females of different octopus species may have unique chemical signatures, and males' receptors may be tuned to respond only to the right blend of hormones. If so, this mating strategy could help keep species separate and potentially give rise to new ones. "Species boundaries are shaped not only by the genes organisms carry but by the molecular systems that determine how organisms perceive one another," Anna Di Cosmo, a zoologist at the University of Naples Federico II in Italy, writes in a commentary accompanying the new study. "By reshaping perception, evolution reshapes reproduction, which reshapes the tree of life."

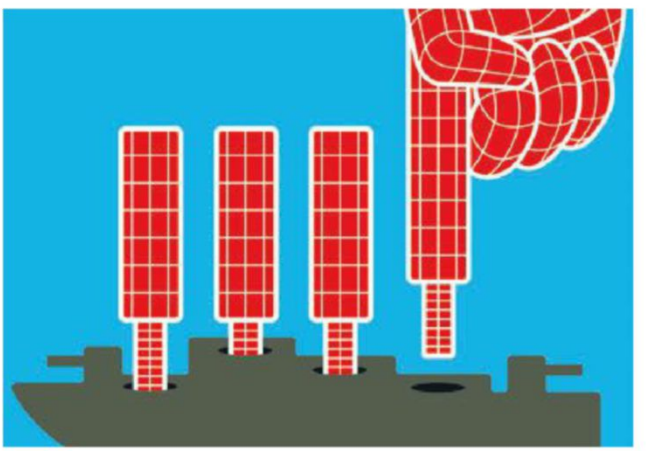
Elena Gracheva, a neurophysiologist at the Yale School of Medicine, who was not involved in the new study, says it's too soon to tell whether all octopuses mate in this way or what role these sensory systems may play in evolution. She is impressed by the thoroughness of the research, however, which began with a naturalistic observation and proceeded all the way to fine-grained molecular analyses. "You have very striking animal behavior, and then you're going down to the single molecule, which I think is beautiful," she says. "But I would say that this is just the beginning of the discovery."

—Cody Cottier

TECH

Battleship Science

Game-playing AI can show us how to do science better



IF ARTIFICIAL INTELLIGENCE IS GOING to revolutionize the way science is done, as many of the frontier AI laboratories hope, it needs to master board games first. That's the lesson from a recent study of AI models' decision-making skills, tested with the game Battleship. The goal was to find ways for models to be more careful with limited resources: "cheap interventions" for information seeking, as research scientist Valerio Pepe puts it.

Science requires lots of decisions—researchers must choose which hypotheses to pursue and which simulations to run. The choices will determine which path to follow when resources for experiments are limited. "You can get only so much data because getting data is either expensive or time-consuming," says Pepe, who led work on the project before joining OpenAI. In April, Pepe and his colleagues presented their findings at the International Conference on Learning Representations, an annual meeting dedicated to AI deep learning.

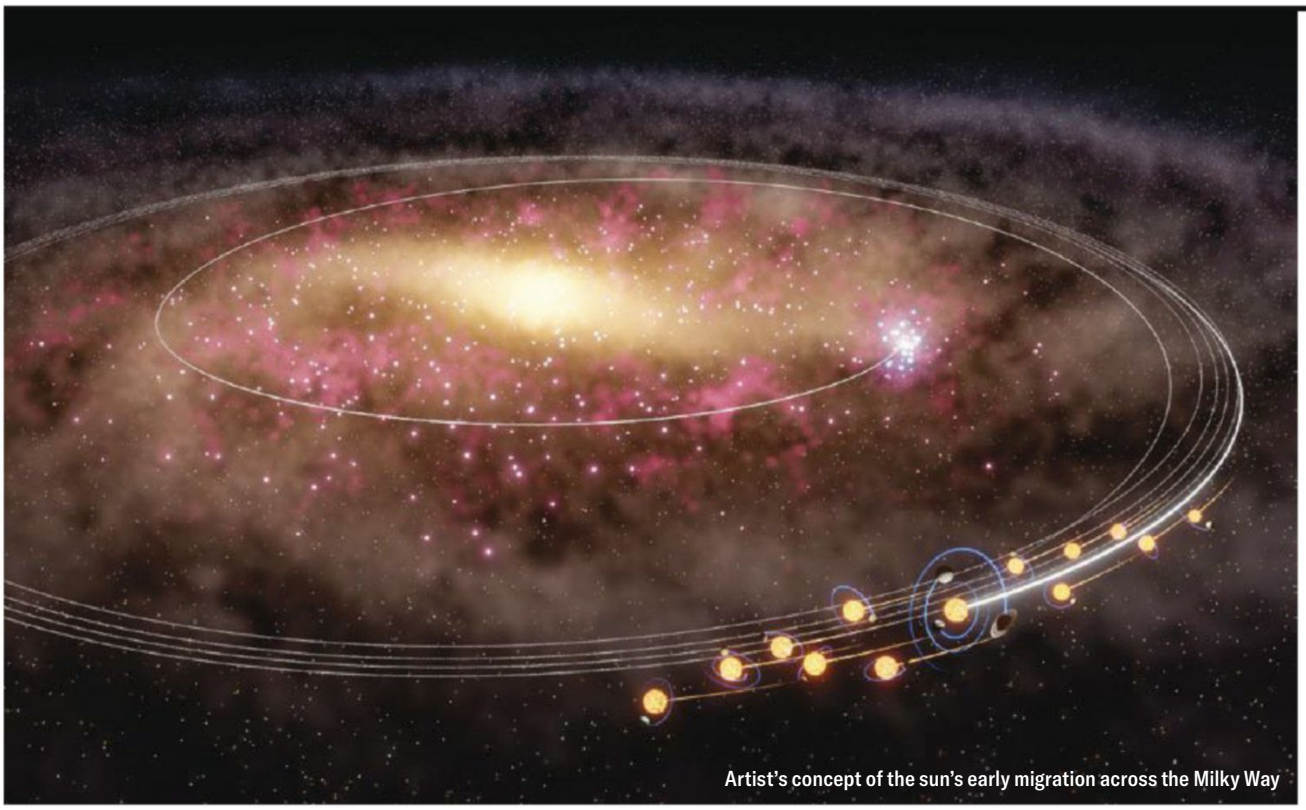
The researchers designed a collaborative version of Battleship that could be played by humans or AI. In the game, one team member generated questions about the map of ships' locations while another answered them, in a combined effort to pinpoint where the vessels were hidden and sink them. By counting how many rounds it took to sink all the ships, the researchers could test how large language models (LLMs) performed compared with other LLMs and with the 42 human players the group had enlisted. Initially, humans consistently won in fewer moves than Llama-4-Scout, Meta's efficiency-focused AI model. OpenAI's premier reasoning model, GPT-5, performed better than both.

The scientists were inspired by Bayesian experimental design, in which researchers interpret decision-making by estimating the likelihoods of events given prior assumptions. They optimized their models to ask questions that maximized the chances of hitting targets accurately and the amount of information they gained with each question, as well as to look ahead a turn when deciding which move to make. The scientists also found that accuracy increased when the players communicated with snippets of code rather than natural language. Through this process, the group led Llama-4-Scout to win in fewer moves than GPT-5 two thirds of the time at about one hundredth of the cost. On average, it also won in seven fewer moves than the human players.

Battleship is much simpler than many problems in science—chemical and biological samples, for instance, can't be interpreted as clearly as Battleship boards. But Pepe says the methods AI used in the game will probably also be applicable to scientific decision-making.

"The framework will be very useful to measure whether language models are really making progress" in deciding which hypotheses to pursue among all possibilities, says Yuanqi Du, a researcher focused on AI for chemistry who recently completed his Ph.D. at Cornell University and was not involved in the study. "Understanding the whole hypothesis space you're searching, that's the hardest part." *—Peter Hall*

Illustration by Thomas Fuchs



Artist's concept of the sun's early migration across the Milky Way

NAOJ

ASTRONOMY

Stellar Caravan

The sun traveled across the Milky Way alongside thousands of stars

OUR SUN WAS BORN 4.6 BILLION YEARS AGO near the crowded center of the Milky Way and then migrated roughly 10,000 light-years outward to the peaceful galactic suburbs it currently occupies. Now a pair of recent studies in *Astronomy and Astrophysics* argues that the sun did not make this trip alone.

Details of the sun's journey can be found in its chemical composition, says Tokyo Metropolitan University astronomer Daisuke Taniguchi, a co-author on both studies. "Astronomers know that the sun's birthplace lies closer to the galactic core than its current position," Taniguchi explains. The Milky Way's dense inner regions formed stars faster and accumulated heavy metals far more quickly than the outer edges—and a star with the sun's age and chemical components would not have been able to form at its present location. But getting there required crossing a dramatic border.

Milky Way observations have revealed an enormous rotating barlike structure made of gas, dust and millions of stars that slices through our galaxy's center. This bar creates a distinct gravitational phenomenon known as the corotation barrier, which prevents inner stars from traveling to the galactic outskirts. Computer simulations suggest that only about 1 percent of stars born at the sun's presumed original location could successfully breach this barrier to reach our present neighborhood within a 4.6-billion-year time frame. Yet Taniguchi and his colleagues discovered that thousands of "solar twin" stars, each with a mass and a metal makeup similar to those of the sun, managed to do so.

To catalog these stellar migrants, the researchers turned to the European Space Agency's Gaia satellite, an observatory tracking the positions, movements and light wavelengths of more than two billion stars. They identified 6,594 solar twins within about 1,000 light-years of Earth.

When the scientists looked at the age distribution in their catalog, they saw two distinct peaks: one narrow spike of stars around two billion years old that probably formed locally and a broad, massive grouping of stars between six billion and four billion years old that included our sun—"a large population of stars that migrated from their birthplace to their current position," Taniguchi proposes.

Alice C. Quillen, a physicist and astronomer at the University of Rochester, who was not involved in Taniguchi's studies, warns that there's a chance that the broad peak of solar twins might be an artifact resulting from the sample-selection method—a mere statistical illusion. "The sample is distance-limited, and most of it would be stars that make it into the solar neighborhood," Quillen says. This factor could favor stars with more oblong orbits, which tend to be older, because younger stars with circular orbits wouldn't have made it to

our vicinity yet. But Taniguchi says his team addressed this bias and found no strong effect of age on the distribution of orbital shape among the solar twins.

His team proposes that the corotation barrier did not stop the migration of the sun and its cohort, because the barrier was not fully formed when it happened. In fact, Taniguchi suggests, the growing galactic bar could have pushed the migration forward instead of restricting it. The sun and its thousands of solar twins could have been propelled by the combined gravitational forces of the forming bar, the Milky Way's spiral arm structure and, most likely, close passages of the nearby Sagittarius dwarf galaxy.

Rosemary Wyse, an astrophysicist at Johns Hopkins University, who was not involved in the studies, says that the researchers' argument is persuasive but adds that (as the study authors note) the exact timescales remain uncertain. "The field of galaxy dynamics is itself dynamic," she says.

—Jacek Krywko

ANIMAL SENSING

Nocturnal Navigation

These ants use a sophisticated lunar compass

WHEN THE SUN SETS, millions of nocturnal ants awaken ready to eat. Some species forage all night, traveling from nest to food source and back again, often following trails they mark with scent. Scientists assumed bull ants, which don't rely primarily on scent navigation, had to wake up before dark and use the day's last light to find their way to sustenance. But a new study of one bull ant species shows the insects continue to navigate when the sun goes down—using an innate lunar compass.

Just as diurnal ants follow the relatively steady movement of the sun, the bull ant species has adapted to the orbiting moon's constant changes, according to research published in *Current Biology*. The ants use what the researchers call time compensation: they keep track of how much time has passed since they left the nest to gauge where the moon should be in the night sky, much like early human navigators used the North Star.

"It was an area where we didn't really know what was going on" until now, says lead study author Cody Freas, an entomologist at University of Toulouse in France. "These ants use a lot of different cues at the same time, and that helps them in case one cue becomes unreliable."

The researchers captured the insects en route to their usual feeding areas and put a subset into darkened boxes that lacked any environmental cues about time passing. (They put others in transparent boxes.) After several hours the scientists released the ants in a new location and watched them try to find their way to food. When held in darkness for long enough that the moon moved significantly, the ants veered off course, suggesting its position was their main cue.

"This is just a little bonkers," says Rodolfo da Silva Probst, an entomologist at the University of California, Davis, who was not involved in the study. "They need to compensate for the trajectory of the moon. I mean, I don't know how to do that."

Other nocturnal creatures, including sand hoppers and moths, are thought to use the moon's position to find their way, but these bull ants are the first found to have such an intricate, time-linked approach to lunar navigation. Additionally, researchers learned that the ants combine their impressive lunar compass with terrestrial and solar cues, at dawn and dusk, to navigate consistently even as moon visibility varies during the lunar month.

There are more than 12,000 ant species in the world, and they all do things a little differently, but figuring out how one species has adapted to its unique ecological niche might help researchers understand others, da Silva Probst says. "Maybe by studying other nocturnal ants, you might discover other mechanisms." *—K. R. Callaway*

Ajith Gopinath/Getty Images

Ants show newfound lunar navigation skills.

MICROBIOLOGY

Microbe Metropolis

Sinking microbial cities may solve a key ocean mystery

WHEN "MARINE SNOW" made of dead plankton's shells, fish poop, dust particles, and other debris descends to the ocean floor, it carries atmospheric carbon the plankton used to make their calcite shells. It's one of the ways the ocean stores carbon, helping to keep greenhouse gases from turning the planet into an oversize toaster oven. Yet scientists realized that something has been dissolving those calcite shells and releasing carbon dioxide, reducing the ocean's carbon-trapping capacity. A study published in the *Proceedings of the National Academy of Sciences USA* identified the culprit: dense microbe "cities" living inside the marine snow.

The individual cities are microscopic, but collectively they have powerful effects on Earth's climate because the ocean is home to an inconceivable number of microbes. A shot glass full of seawater can contain millions of bacterial cells. "If you were to take every bacterial cell in the ocean and string them end to end like a chain of pearls, it would stretch 50 times around the Milky Way," says study co-author Andrew Babbin, an oceanographer at the Massachusetts Institute of Technology.

To study the microbial cities, "we brought the ocean into the laboratory," says Benedict Borer, lead study author and a biogeochemist at Rutgers University. The scientists introduced microbes to a microfluidic chip designed to mimic marine-snow particles and added fluorescent molecules whose glow changed with oxygen levels and acidity. (The system was so sensitive that at first, people breathing in the lab were affecting measurements.)

The researchers found that the cities' chemical microenvironments increase calcite dissolution. Many oxygen-breathing microbes feed on carbon, then release carbon dioxide, which turns into carbonic acid in seawater. The sheer number of microbes breathing in such tight quarters creates concentrated pockets of carbonic acid in and around the marine-snow particles, which dissolve the snow's calcite.

As marine-snow particles dissolve and get lighter, they also sink more slowly, the researchers say, giving carbon extra time to escape before it can reach long-term storage in the deep ocean and potentially increasing its release back into the environment. More research is needed to calculate microbial cities' full influence on ocean acidity because dissolved calcite can counteract the carbonic acid to an extent.

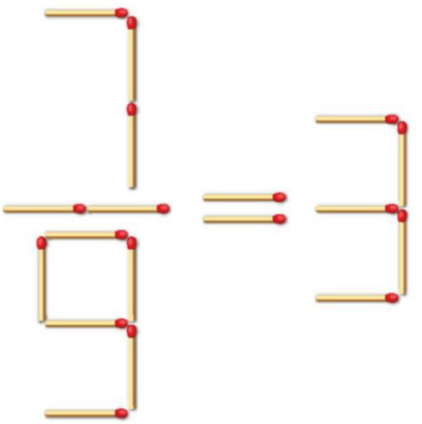
"Large-scale biogeochemical processes often depend on very small-scale interactions," says Hongjie Wang, an oceanographer at the University of Rhode Island, who was not involved in the study. Babbin agrees: "Ultimately everything that's happening at these microscales—that's really what's terraforming our planet." —*Damien Pine*

MATH PUZZLE

Fix the Equation

By Heinrich Hemme

Move two matchsticks to make this equation correct.



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

Spektrum der Wissenschaft; Translated with the assistance of artificial intelligence (*math puzzle*)

Illustration by Thomas Fuchs, Graphic by Amanda Montañez

SCI AM

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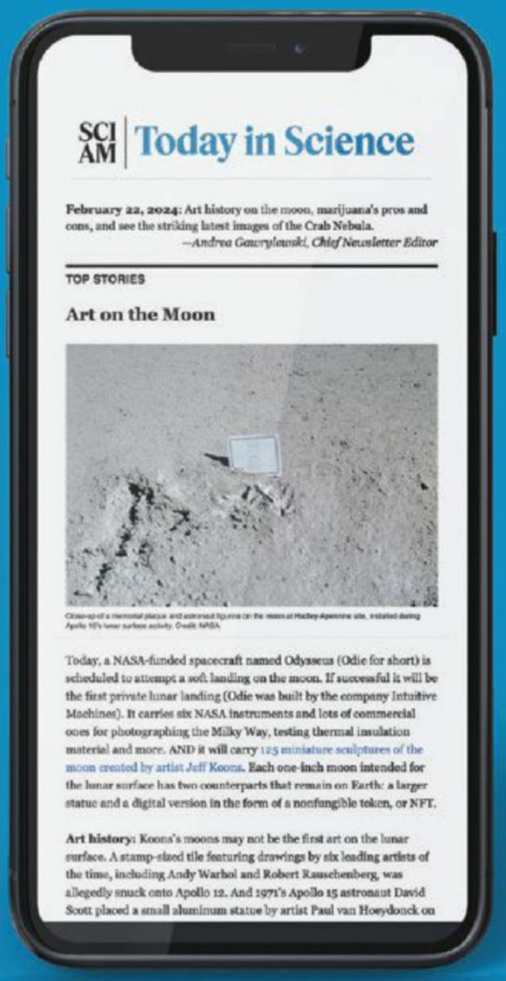

The Fusion Wager

Helion is trying to turn a pulsed-plasma machine into a power plant—on a start-up timeline BY ALEX PASTERNACK

JUST EAST OF MALAGA, WASH.—a farm town in apple country—the Columbia River runs between basalt bluffs past the Rock Island Dam, which has turned water into electricity for the Pacific Northwest since 1933. Now, on a flat stretch of land nearby, a very different kind of power project is taking shape.

Helion Energy, one of the world's best-funded private fusion companies, is building what it calls Orion: a machine it says will become the world's first fusion power plant, delivering 50 megawatts of electricity to Microsoft data centers by 2029. In a field long dominated by laboratory milestones and moving timelines, Helion, backed by the likes of OpenAI CEO Sam Altman, is the first fusion company to make a commercial promise, one that provides a useful lens on the new industry: well-funded, ambitious and entangled with artificial intelligence's huge appetite for power.

"The pressure's on for Helion and everyone else," says David Kirtley, Helion's CEO. He has a ready reply to the old joke about fusion always being 20 years away. "I say, 'We're 20 years late. We need to step up and build these [plants] and deploy them at scale.'"

Private money has flooded the field. Big tech companies are signing power deals with fusion firms years before any commercial machine has delivered electricity. AI is not the only reason for this rush, but it has sharpened the urgency. Data centers require staggering amounts of around-the-clock electricity; fusion start-ups are selling a path to firm, carbon-free power. "It's a situation that's certainly unlike any other energy technology," says Troy Carter, director of the Fusion Energy Division at Oak Ridge National Laboratory—and, he adds, "maybe unlike other technologies."

But you can't buy your way around the laws of physics. Even as the walls at the Orion site rise, big questions swirl over the company's bold promises—including from one of Helion's co-founders.

Fusion happens in stars all the time. But doing it on Earth is harder: first, you must heat light nuclei into plasma at temperatures above 100 million degrees Celsius, then keep them hot, dense and stable long enough for sufficient reactions to occur. That's the first challenge.

Fuel and materials pose more hard problems. The most practical fusion fuel—deuterium and tritium, both hydrogen isotopes—throws off fast neutrons that bombard their surroundings, degrading the very machine meant to contain the reaction. And tritium is radioactive, with a relatively quick half-life of 12 years, and barely exists in nature. Any reactor running on deuterium-tritium fuel will need to breed its own tritium supply—one of a number of burdens that, as Carter says, the industry has yet to seriously address, leaving them to hope the national labs will carry that load.

Helion, based in Everett, Wash., is betting on one of the more obscure fusion ideas: a linear reactor built around a plasma shape called a field-reversed configuration, or FRC. Unlike the doughnut-shaped steady-state plasma that forms inside a tokamak or the asymmetrical ribbon of plasma coursing around a stellarator, an FRC plasma, resembling a spinning smoke ring, holds itself in place, requiring fewer external magnets. An FRC reactor "has very few external magnets," Carter says. "The magnets you need are much less complex, much lower field and less costly." The catch is confinement: FRC plasmas are notoriously hard to stabilize as they take in more energy.

"The unique thing about FRCs: We call them 'self-organized,'" says experimental physicist John Slough. "It's like spinning a top." But "if you try to screw around with it, you're just going to mess it up."

Slough spent decades working to keep the idea alive. By the early 2000s federal support for alternative fusion concepts had largely dried up; Slough, then at the University of Washington, continued on a shoestring, with small space-propulsion contracts from NASA and the U.S. Air Force. A key insight was that two FRC plasmoids could be formed with

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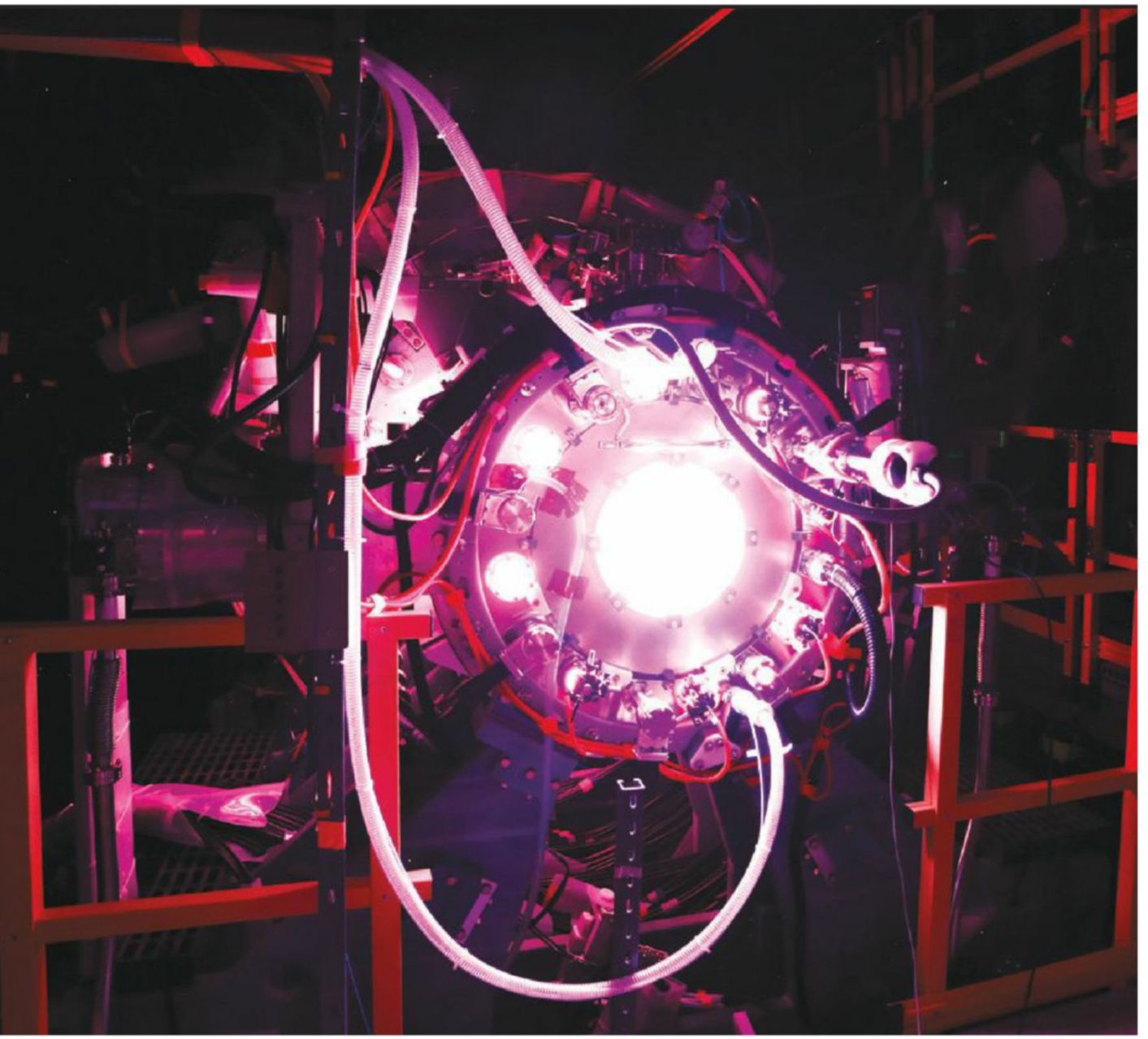


Helion

Polaris, Helion's seventh-generation prototype, glows pink during recent testing with deuterium-tritium fuel, signaling that a thermonuclear reaction is underway.

magnetic pulses at either end of the reactor, accelerated toward each other at up to 1.6 million kilometers per hour, and made to collide and merge—using the collision itself as a shortcut to fusion temperatures. The reaction takes place in fractions of a millisecond: through a rapid stream of pulses, the fuel is heated, compressed and expanded repeatedly to generate electricity.

Around 2008 Slough hired Kirtley, then a young aerospace engineer, at MSNW, his small R&D company. As federal support ebbed, Kirtley saw something Slough did not: the seed of a start-up. They and an engineering technician named Chris Pihl worked on the idea. With Slough's blessing, Kirtley and Pihl took the concept to start-up incubator Y Combinator (then run by Altman), and Helion took off. It was part of a pattern in fusion: when public money dried up, some abandoned concepts turned into start-ups.

Another unusual feature of Helion's approach is what comes after the reaction. Most fusion power plant designs call for using fusion heat to boil water, spin a turbine and drive a generator. Helion is skipping that thermal cycle. As the merged plasma expands after the fusion pulse, it should push back against the magnetic field and induce electric cur-

rent directly in coils surrounding the machine. Helion claims that when the plasma generates current directly, it can recover electricity at efficiencies over 95 percent. That number matters enormously.

"Fundamental to our technology is direct electricity recovery," Kirtley says. "If you can recover the electricity at 95 percent efficiency, fusion has to do only that [last] little bit." Carter agrees that this aspect is Helion's clearest technical edge—if it works. "That's a real advantage for Helion," he says, which "does lower the bar, if they can do that, on how much gain they need."

THAT "IF" IS THE WHOLE STORY. Helion has built seven prototype machines, each more powerful than the last. The latest, Polaris, is a 19-meter device with capacitor banks capable of storing and delivering a staggering 50 megajoules of energy per pulse. Earlier this year Helion announced that Polaris, housed in a 30,000-square-foot facility in Everett, had reached a record 150 million degrees C and, according to the company, had become the first privately developed fusion machine used to "demonstrate" fusion using deuterium-tritium fuel.

The engineering challenges have been brutal. Helion has had to replace research-grade switches with solid-state hardware that can survive hundreds of millions of pulses. To power the machine, the company also has constructed thousands of specialized high-voltage capacitors; Polaris requires enough of the oil-filled devices to fill 150 shipping containers. Through each rapid repetition, all the electrical systems must work in perfect synchrony, with nanosecond timings. Each pulse appears as "this flash of light, like a camera flash," says Anthony Pancotti, a Helion co-founder. "It produces fusion, recovers that energy, before you can blink your eye."

You can't buy your way around the laws of physics.

This approach shapes Helion's manufacturing ambitions. It imagines many modular generators, built in factories and shipped to customers like server racks for energy. The company now employs around 600 people, with a heavy emphasis on technicians rather than scientists.

In 2023 Helion announced what it called the first power purchase agreement in fusion, committing to open its Malaga plant by 2028 and supply Microsoft with 50 megawatts of electricity by the following year, with financial penalties for nondelivery. A few months later it announced a 500-megawatt development deal with steelmaker Nucor. Altman recently stepped off the company's board as OpenAI and Helion explored a possible partnership.

But a power deal is not the same thing as a working power plant. Helion's history, like that of many fusion projects, includes a string of missed deadlines. The company once projected net electricity from an earlier machine by 2024. As the Microsoft date looms, no published results have confirmed net power generation from Polaris.

The sharpest criticism comes from Slough, whose FRC research helped to give rise to Helion. He has since split with the company, and his objection goes to the heart of the design. The core problem, he says, is the same one FRCs have always faced: confinement. In his view, Helion's aggressive approach of firing plasmas together at extreme speed and compressing them drives instabilities severe enough to produce a "catastrophic" loss of flux before fusion can do the work Helion needs it to do. At those speeds, he says, "you've run up against a fundamental aspect of the FRC."

Helion's longer-term ambition draws a second line of criticism. The company ultimately wants Orion to run on deuterium and helium-3, which would produce fewer higher-energy neutrons and maximize its direct capture of electricity. But helium-3, produced by the radioactive decay of tritium, is exceedingly scarce, and fusion reactions are harder to achieve, requiring temperatures of about 200 million degrees C. Slough says that the heat and confinement it would require are physically implausible with Helion's design. Where he once saw possible pathways, he now "can't see anything in the physics" that would allow it.

Kirtley counters that Slough relies on "dated" one-dimensional models that ignore the speed of its pulses. "Many instabilities do not have enough time to grow," he says, arguing that Helion's machines remain stable enough to complete formation, merging, compression and fusion on the required timescale. Helion plans to breed helium-3 from tritium and says that its models suggest it can convert more than 85 percent of the plasma's energy into useful electricity.

There is also the question of transparency. Helion publishes very little peer-reviewed data about the core performance of its plasma, making it difficult for outside scientists to evaluate its claims. "They don't publish, and that's a stance they take,"

Trenta, Helion's sixth-generation prototype, produced plasma temperatures of 100 million degrees Celsius during testing—a record for a private fusion machine.

Helion

Carter says. Without more data, he adds, "it is hard to fully assess where they're headed."

Another line of scrutiny comes from Karl Lackner of the Max Planck Institute for Plasma Physics in Germany, whose group published formal comments in the *Journal of Fusion Energy* in February. Their target is a 2023 paper by Kirtley and Helion scientist Richard Milroy, laying out the physics case for the company's deuterium–helium-3 approach. Central to its projected energy gains is the idea that ions in the plasma can remain far hotter than electrons after the collision and compression—a condition that would reduce the energy input required to sustain the reaction. Lackner's group argues that once you account for ordinary collisional power transfer, the requirements become "much more demanding" than Helion's analysis suggests.

For its part, Helion says Lackner's analysis does not account for the cadence of its pulses. A favorable ion-electron temperature ratio improves efficiency, but the question "is not whether ions can remain hotter than electrons forever but whether the pulse evolves quickly enough" for that nonequilibrium to support efficient fusion and energy recovery.

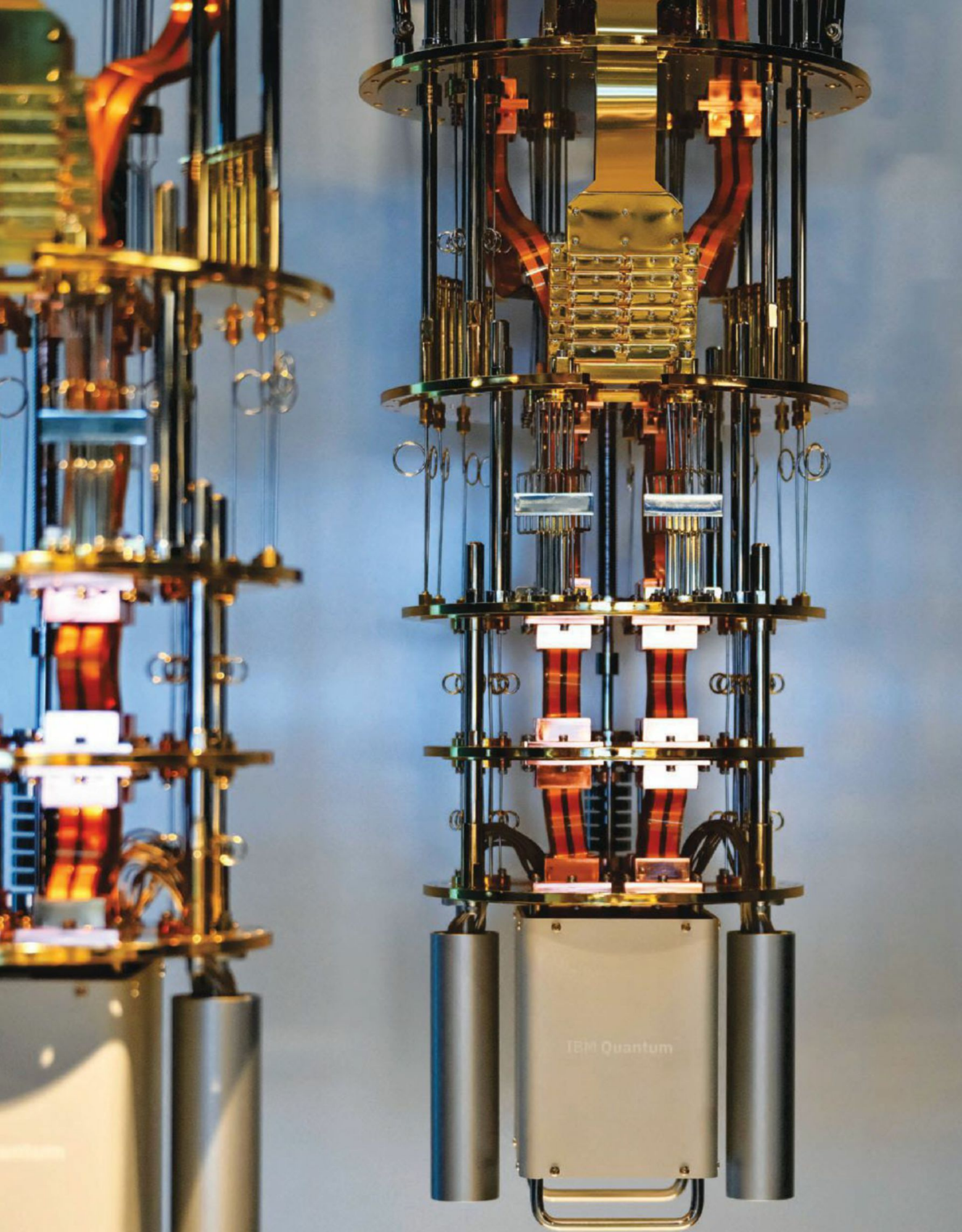
NONE OF THIS means Helion will fail. Fusion has a long history of overpromised deadlines and delayed breakthroughs. But private fusion has changed the field's pace, forcing questions about supply chains and manufacturing into a domain that for decades focused on lab science.

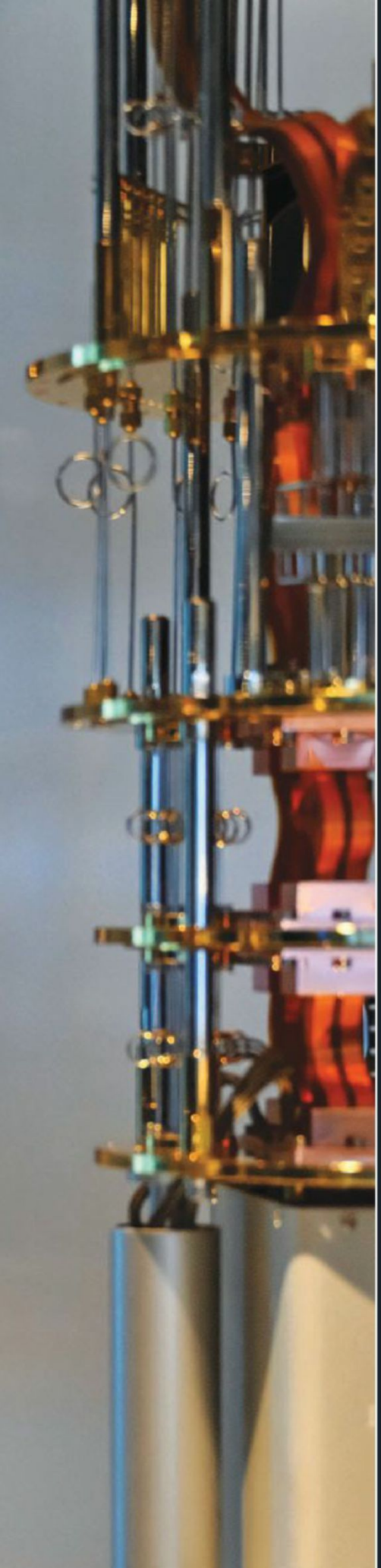
Carter, whose 2021 U.S. Department of Energy report set a 2040 target for the first fusion pilot plant before private capital accelerated the timeline, thinks a pilot plant in the 2030s is feasible. But he is emphatic that no one company can get there by itself.

The supply-chain dimension alone illustrates why. Helion makes its own capacitors and ultra-high-pressure ceramics; other fusion companies need similar components. Massachusetts-based Commonwealth Fusion Systems is building infrastructure to produce the high-temperature superconducting magnets it needs. But no start-up can fully internalize these industrial-scale obstacles on its own. In April the DOE said it will invest $135 million—its largest fusion investment to date—to address the "toughest technical barriers" to commercial-scale fusion. "If there's a way for the public sector to support these supply-chain gaps," Carter says, "that's something we should be looking at."

Back near Malaga, the construction continues. Orion is rising on the plain above the Columbia. Not far away, Helion is preparing a new assembly facility to piece together thousands of intricate components. A short distance downstream, the dam still turns the falling water into light.

Whether Helion will deliver by 2028 is uncertain, as is fusion's ability to make a meaningful contribution to the grid in the 2030s. The physics still have to cooperate. But by treating fusion as a manufacturing challenge rather than a mainly scientific one, Helion has already changed what the industry believes is possible—and how soon. ●





Angela Weiss/AFP/Getty Images

THE QUANTUM REVOLUTION

Will computers based on quantum physics change the world?

BY ADAM BECKER

INSIDE A LOW-SLUNG BUILDING IN AN OFFICE park near the southeastern edge of the San Francisco Bay, a cluster of white tanks sit bathed in blue light. Within these tanks are sets of superconducting circuits etched into chips, all held by golden chandelierlike structures and cooled by liquid helium and liquid nitrogen. The superconducting chips are fabricated in the clean room next door, where white-suited figures work with room-size machinery, fume hoods and acid baths. The facility—the chips, the tanks, the clean room and the enormous reserves of liquid nitrogen behind the building—are all deployed in service of a single dream: quantum computers.

The IBM Quantum System Two, a modular quantum computer, as seen in 2025 at the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y.

This location is the main fabrication plant for quantum computing company Rigetti Computing in California; each refrigeration tank contains one of Rigetti's top-of-the-line quantum processing units. One day quantum computers will be able to perform certain kinds of computations orders of magnitude more quickly than the classical computers all around us, experts hope. "We're talking a million [or a] billion times faster at a very, very small fractional energy consumption," Rigetti's CEO, Subodh Kulkarni, tells me. "That's the beauty of quantum computing. We can potentially solve problems that are unsolvable today."

Rigetti is just one of dozens of outfits hoping to capitalize on the possibilities. Over the past 20 years start-ups such as Rigetti and giants such as IBM and Google have invested big money in quantum computing—$1.2 billion from venture capitalists in 2023 alone. It's a major subject of research at universities and government laboratories around the world. All of them are chasing the dream, but the details of that dream depend on whom you ask. Venture capitalists and other purveyors of Silicon Valley hype are promising that quantum computing will supercharge artificial intelligence, or vice versa, but experts are unconvinced of these claims. Kulkarni and others talk about quantum computers revolutionizing drug discovery, weather forecasting and the financial industry. Governments prize their promised abilities to crack heretofore unbreakable codes.

But none of these predictions are certain. Quantum computing is reaching its make-or-break moment: Scientists hope that in the next few decades they'll be able to scale up today's quantum systems to the size needed to make real breakthroughs and finally beat classical machines at useful tasks. If they can do that, quantum computers may change the world in all kinds of ways. But plenty of obstacles stand in the way, and until quantum computers can overcome them, we won't know what they're really capable of.

Adam Becker is a science journalist with a Ph.D. in astrophysics from the University of Michigan. He is author of, most recently, *More Everything Forever: AI Overlords, Space Empires, and Silicon Valley's Crusade to Control the Fate of Humanity* (Basic Books, 2025). He hosts the podcast Dreaming against the Machine.

A Rigetti quantum computer, shown at the Nvidia GPU Technology Conference in Washington, D.C., in 2025, uses superconducting qubits.

Kent Nishimura/Bloomberg/Getty Images

WHAT, EXACTLY, IS A QUANTUM computer? It's tempting to say it's a computer that runs on the principles of quantum physics. But that isn't adequate—quantum physics governs the behavior of all matter, so all computers would be quantum computers by this definition. Similarly, it's not enough to say a quantum computer is a computer that takes advantage of quantum phenomena in its operation. Nearly all computers today run on silicon transistors, the workings of which we can understand only through quantum physics.

To truly answer the question of what makes quantum computers quantum—and why they're so hard to build—we need to talk about Schrödinger's cat. In the original thought experiment developed in the 1930s by Erwin Schrödinger, one of the founders of quantum mechanics, the famous feline is sealed in a box with a lump of radioactive metal, a vial of poison, and a contraption that will smash the vial if it detects any radiation from the metal, killing the cat. Quantum physics dictates that if you leave the box sealed for a certain amount of time, there will be a 50–50 chance that the metal lump will have emitted some radioactivity. But, crucially, until someone measures the radiation, the lump is in a superposition: a state in which the radiation has been both emitted and not emitted. And that means the vial of poison will be in a superposition of smashed and intact.

The cat will therefore be in an equal superposition of dead and alive until you open the box and see which way things have gone. (What constitutes a "measurement" in quantum physics is a separate and thorny question that people, including me, have written entire books about.)

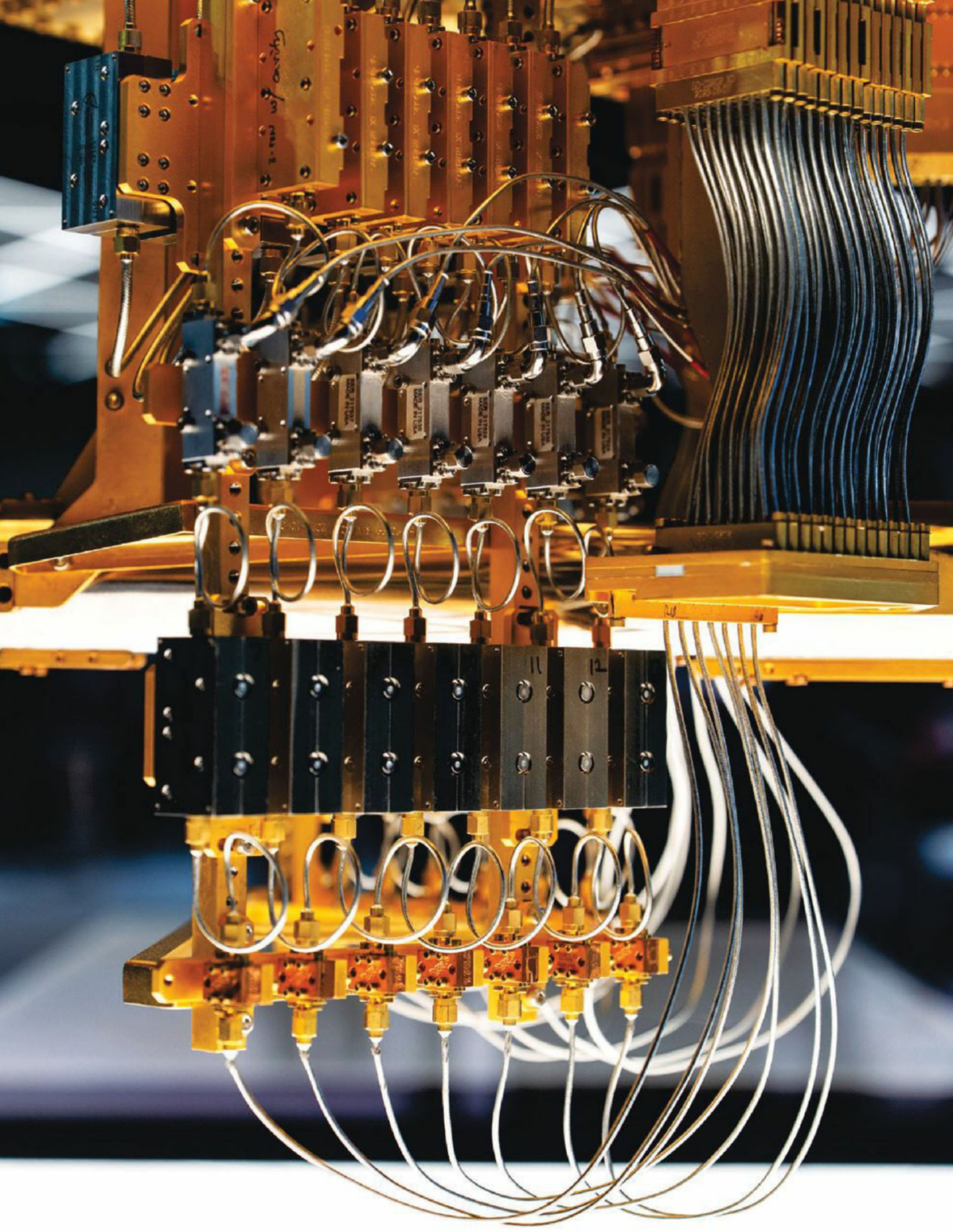
Now imagine that you opened the box slightly earlier, perhaps out of anxiety for the poor creature. In that case, immediately before you opened the box, the cat would still have been in a superposition of dead and alive but with more "aliveness" in the superposition than "deadness." By waiting the right amount of time, you could put the cat into any superposition you like with any share of aliveness and deadness.

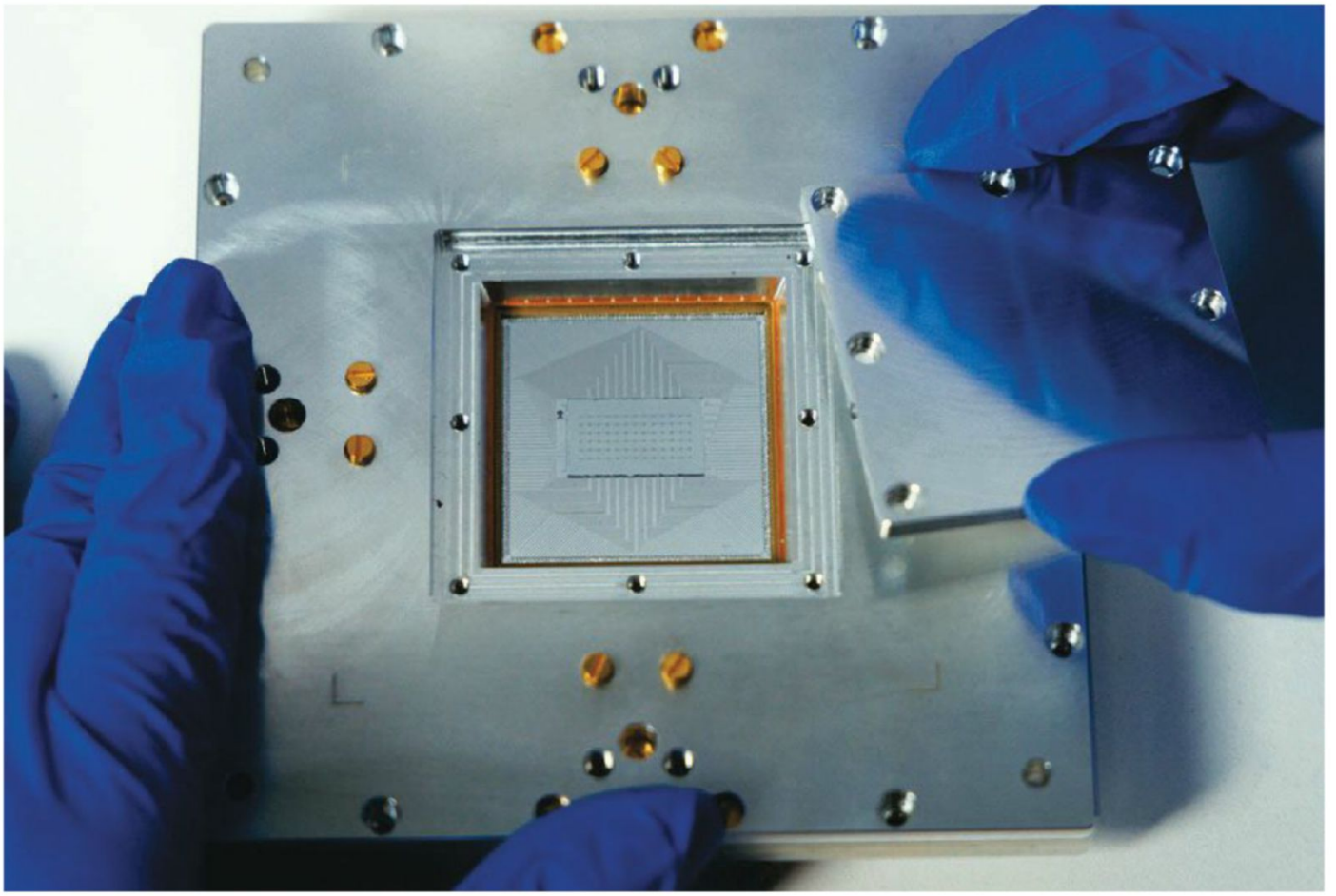
Tunable superpositions such as this one are what make a quantum computer quantum. Conventional computers use their transistors to carry out computations using bits that can be in one of two states: zero or one. Quantum computers use quantum bits, or qubits, which have more options available to them. Like Schrödinger's cat, qubits can be in any superposition of zero and one.

Qubits have something else in common with the unfortunate feline. When it's trapped in the box, Schrödinger's cat becomes entangled with the rest of the box, meaning its quantum state becomes tied up with the quantum states of the lump of metal, the detector contraption and the poison. Similarly, quantum computers must entangle their qubits to perform calculations with them. But whereas the entanglement between the cat and everything else in the box happens in an uncontrolled way, a quantum computer must keep strict control over its qubits' entanglement with one another: which ones are entangled, how much and in what way.

This combination of qubits controllably entangled with one another is what allows quantum computers to do tricks typical computers can't, at least in theory. One of the most touted, for a big-enough quantum computer, is the ability to calculate the factors of very large numbers much faster than a standard computer can by using a technique called Shor's algorithm, after Massachusetts Institute of Technology theoretical computer scientist Peter Shor, who invented it in 1994.

"Faster" is a bit of an understatement: theoretically, using Shor's algorithm, a quantum computer could factor in sev-





The Chuang-tzu 2.0, a two-dimensional superconducting quantum computer, uses 78 qubits in its calculations. The processor was built at the Chinese Academy of Sciences Institute of Physics.

eral days a number that would take a nonquantum supercomputer millions of years. This impressively speedy algorithm may sound like a niche application, but the fact that it's incredibly time-consuming for conventional computers to factor large numbers is the basis of most modern encryption, especially the kinds of encryption used on the web. A quantum computer, then, wouldn't just be a good code breaker—it could potentially break the cryptography underpinning the entire Internet. Unsurprisingly, developing quantum computers has become a priority for the security apparatuses of governments all over the world.

Quantum computers also might be able to use their impressive control of their own qubits to mimic nature on a level never possible before, modeling the interactions of atoms and molecules with detail that regular computers, which lack the quantumness of nature, simply can't match. These abilities could lead to breakthroughs in basic physics and chemistry, as well as in applied research for materials science, pharmaceutical drugs, and other fields. And some people, such as Kulkarni, believe that quantum computers also may be able to solve more familiar problems better than classical machines, such as simulating financial markets and Earth's climate.

THERE IS, HOWEVER, A CATCH. Schrödinger's cat became entangled with the rest of the box without making any special effort—entanglement happens naturally between objects that interact with each other in any way. Right now you are becoming somewhat entangled with the air around you, the surface you're sitting or standing on, and the screen or magazine where you're reading these words. This kind of natural entanglement that arises between a quantum system and its environment is known as decoherence.

Decoherence is fatal to a quantum computer's ability to perform calculations. For a quantum processor to keep its vitally important control over its qubits and their entanglement, it must be isolated from the rest of the world while it does its work. It must also maintain a high level of control over the physical interactions among all the atomic components of its own qubits. That isn't easy to accomplish even for a brief fraction of a second. Preventing unwanted interactions among a quantum computer's components is one of the prime hurdles standing between today's relatively modest quantum computers and the larger, more powerful ones scientists and engineers are hoping to develop. One of the main strategies researchers employ is to keep quantum computers very, very cold because heat—the random motion of atoms—creates unintended entanglements.

This challenge is tied up with the biggest open question in quantum computing: What's the best way to make a qubit? Bits in standard computers are made through voltage changes on small electronic gates in a solid-state chip or the magnetic domains on the disk of a hard drive; controlling these bits is impressive

Xinhua/Alamy

and difficult enough. But a qubit must be even more finely controlled: to carry out calculations, a quantum computer must be able to place its qubits into a specific initial quantum state, then control their entanglement by passing them through a sequence of quantum logic gates, all while maintaining their perfect isolation from their environment and preventing them from interacting with one another or with other components of the quantum computer in unwanted ways. For years after quantum computers were first proposed, in the 1980s, some experts were skeptical that they could ever be built. (A minority of researchers still believe that usefully large quantum computers can't be built.) But in the past 20 years scientists have developed working quantum computers, albeit relatively small ones, with no more than several hundred or so qubits. These machines are too simple to perform interesting calculations, such as the advanced trickery of Shor's algorithm or quantum simulations, on anything but small example problems. Scaling them up to more useful sizes means making a bet on the best approach.

Qubits can be made out of many different materials [see "A Qubit Field Guide" on page 92]. Researchers have designed several possible architectures, and there is no agreement on the best option. "There are a lot of ways to do it, and everyone thinks that they have the best way," says Alaina Green, a physicist at the University of Maryland's Joint Quantum Institute.

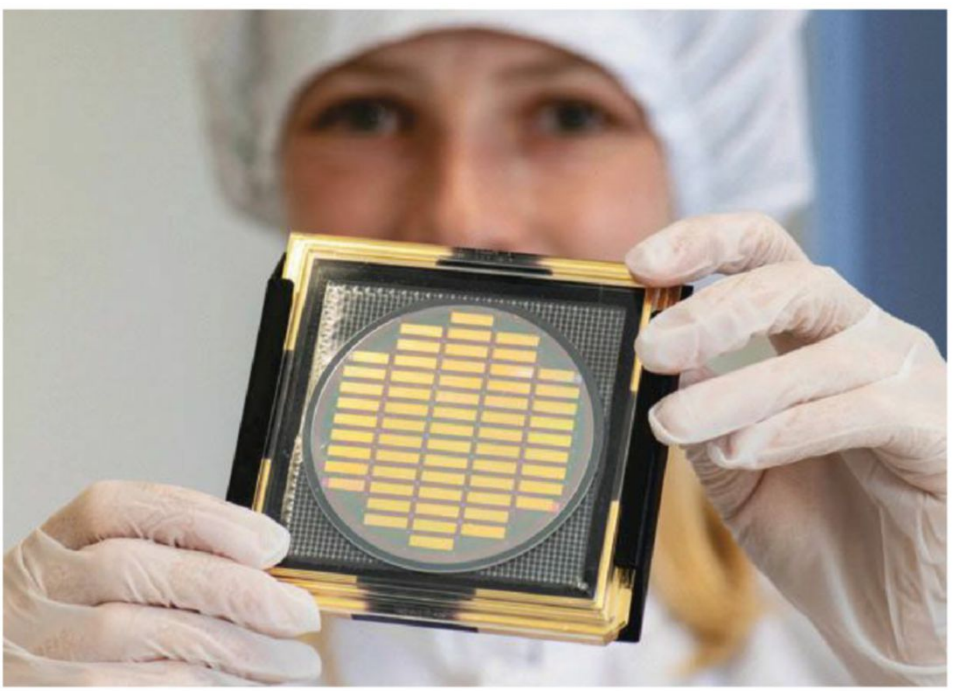
Two of the leading qubit approaches are superconducting circuits and trapped atoms or ions. The former are microscopic electronic circuits made of superconducting materials such as aluminum or tantalum that have no electrical resistance at supercold temperatures. Their advantage is that we can build them using variations on existing technology for computer-chip fabrication, and they can work fast. The disadvantage of superconducting qubits is that each chip is made of billions of trillions of atoms, and even at a hundredth of a degree above absolute zero, having so many atoms around means the chips decohere in tens of microseconds.

The other favored strategy is to build qubits out of individual atoms. This option shines exactly where the superconducting qubits don't: when there's only one atom involved, it's easier to keep it from decohering. Trapped atom or ion qubits can be kept coherent for milliseconds at a time. But individual atoms are slower to work with (and engineers can't piggyback on conventional computer-chip-fabrication technology). The upshot is that both types of qubits are capable of performing roughly the same number of calculations before they decohere, at least for now. Although the most powerful quantum computers today use superconducting qubits, atom and ion approaches aren't far behind.

But ultimately, to fulfill their promise, quantum computers will need to find ways to become at least somewhat more tolerant of lapses in their control. Errors inevitably creep into quantum computations because of decoherence and other unwanted quantum effects. Although there is no way to completely halt decoherence, there is a way to compensate for some errors within quantum computers by using another celebrated result in theoretical quantum computing: quantum error correction. This process, remarkably, makes it possible under certain circumstances to detect and correct an unwanted error in a qubit's state without totally destroying its superposition or entanglement with other qubits—akin to altering the mix of deadness and aliveness in Schrödinger's cat without fully opening the box.

The existence of such quantum error-correction codes makes it much more feasible to achieve the high level of reliability that qubits need to implement Shor's algorithm and perform other complex quantum-computational tasks. But this help comes at a cost. Quantum error correction works by assembling groups of qubits into "logical qubits," building a kind of quantum redundancy into each logical qubit by representing it with many actual physical qubits so that an error in a single physical qubit matters less. For error correction to work well, every logical qubit must be composed of a lot of physical qubits—around 100 to 1,000. And to run Shor's algorithm on any interesting problem, or nearly any other useful application, a quantum computer must have thousands of logical qubits. So for quantum computers to achieve their hoped-for potential, today's systems of a few hundred physical qubits must scale up to millions of physical qubits whose entanglement with

An engineer holds up a quantum processor with photonic chips at technology company Q.ANT in Stuttgart, Germany.



Thomas Kienzle/AFP/Getty Images

one another can be finely controlled.

Yet recent breakthroughs have given some researchers hope that quantum error correction may be possible with significantly fewer physical qubits. In one recent study, researchers at the California Institute of Technology and quantum computing start-up Oratomic proposed a method for quantum error correction requiring only about five physical qubits for each logical qubit, lowering the threshold for implementation of Shor's algorithm to around 10,000 qubits. This study has not yet gone through peer review, but if the results hold, it could be possible to build a quantum computer that can run Shor's algorithm sooner than expected.

Even in that case, however, the big question facing the field will remain: How long will it take for quantum computers to scale up to the point where they are useful? Although conventional computers have grown in power quickly over the past 60 years in accordance with Moore's law—the prediction, named for Intel cofounder Gordon Moore, that the number of transistors on a chip would double roughly every two years—there is no guarantee that quantum computers will follow the same exponential trend. Moore's law isn't an actual law of nature—but the inevitability of decoherence is.

ALL THIS FOCUS ON SHOR'S algorithm isn't just about cryptography and national security. The celebrated algorithm is the only one that scientists are sure will allow a quantum computer to do something far more quickly than a conventional computer can. "People have been looking for other algorithms that are like [Shor's] for a long time, and they haven't found any," Green says. "Like, *none.*" Devising quantum algorithms is hard. Proving those algorithms are significantly better than existing nonquantum algorithms is also difficult, and proving they're better than any conceivable nonquantum algorithm is generally extremely difficult, if not impossible.

Scientists are most optimistic about using quantum computers to simulate the quantum aspects of nature. "The reason that quantum computers were initially proposed is the idea that you can use them to simulate quantum systems," says Ewin Tang, a quantum computer scientist at the University of California, Berkeley. But even with this kind of quantum simulation, it may be that quantum computers can't beat classical ones. "There aren't that many superconcrete plans for what one would do with a quantum computer that gives a provable quantum advantage," Tang says. Green agrees. "Unfortunately, it's harder to make provable statements about quantum simulation definitely being able to improve over classical computing," she says. "But we think it should be true."

Even if quantum computers really are better for simulating some quantum systems, as seems reasonably likely, and even if scientists can devise more algorithms that, like Shor's, show a clear and large advantage over known classical algorithms, quantum computers still won't beat conventional computers at most tasks. "The idea that quantum computers can do anything faster than classical computers—that is just simply not true," says William Oliver, a professor of electrical engineering, computer science and physics at M.I.T. and co-founder of a quantum computing start-up recently acquired by Google. "There are only certain problems, which have a certain internal structure to them, as we understand it today, that allow a quantum computer to take advantage of its quantumness."

In the best-case scenario for quantum computers, they will be specialized devices for solving particular kinds of challenges. In all likelihood, they will be used alongside conventional computers in a data center or supercomputing cluster—but not miniaturized in our cell phones. "The things that quantum computing is good at are just not things that people need to do every day," Green says. In 30 years you might have a prescription drug in your medicine cabinet that was developed by models run on quantum computers—but you almost certainly won't have a quantum computer of your own.

Yet the uncertainties that remain in the field haven't kept the business world from making economic forecasts about quantum computing. In 2024 the Boston Consulting Group projected that quantum computers would generate $450 billion to $850 billion in value by 2040. "Impediments to quantum computing in the near term ... do not threaten the long-term development of the technology or the market," the writers claimed. Yet the same group said its 2021 forecast about value creation based on quantum hardware and software improvements was overly "optimistic."

This kind of confident estimate of where quantum computing is going is hard to take seriously, precisely because, for all of its advances so far, the field is still new and filled with unknowns. "Quantum computing is real, it's happening, and it's going to take time," Oliver says. "It's going to take engineering, and there's still science to do as well. It's not all buttoned up." He estimates that we might have larger-scale quantum computers in about 20 years. "Whatever that time frame is, we will be using them to better understand, from a scientific standpoint, the world around us."

When I asked Green when she expected good quantum computers to arrive, she gave me a blunt answer: "I don't know, and I'm unwilling to make a prediction, and I would be very surprised if you found any [physicist] who would." Still, she's eager for that future, whenever it comes. "There is a class of problems ... [that] we have no chance of ever solving with classical computers," she says. "For me, the most promising application of quantum computing is the prospect of potentially solving those problems."

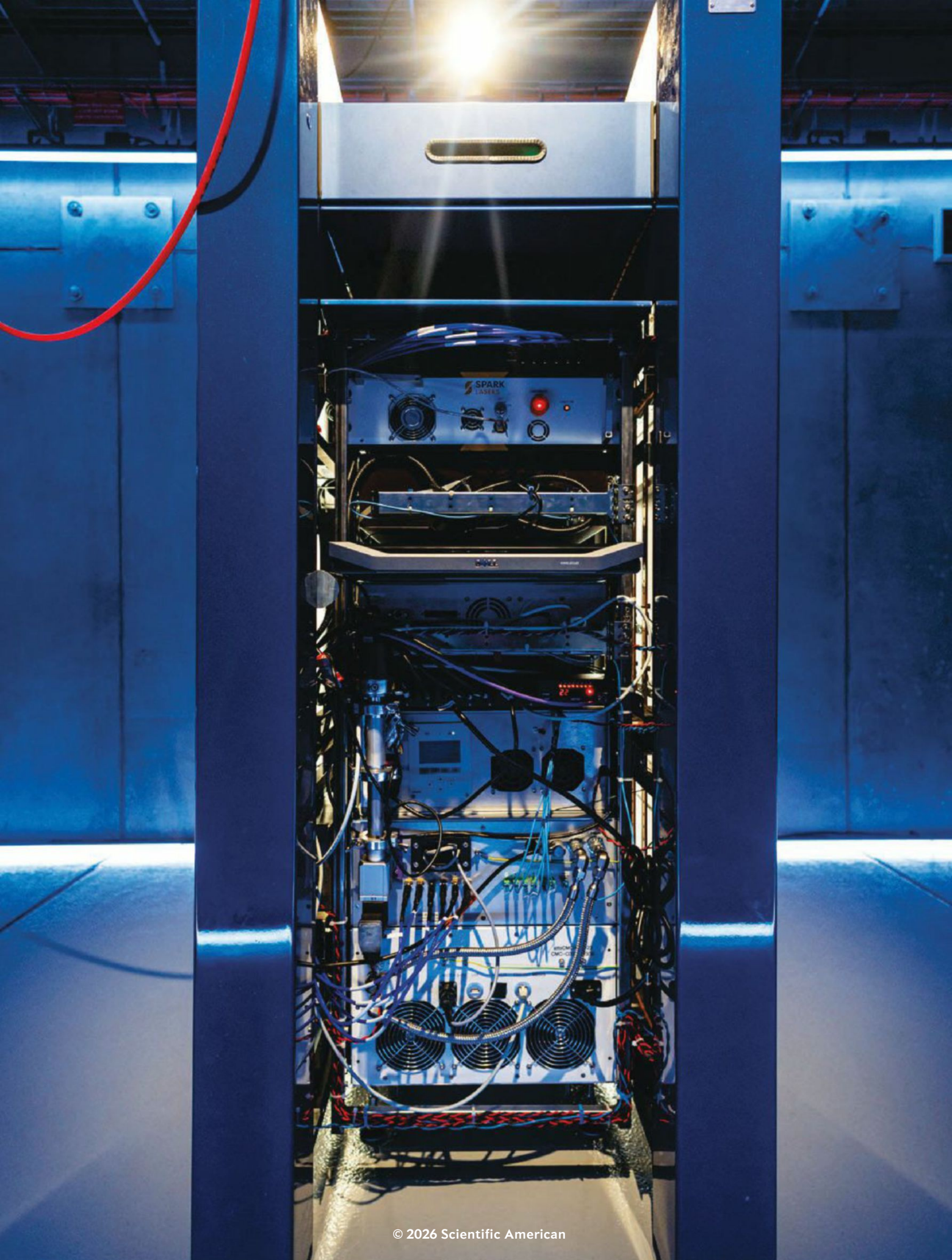
The reality is that we simply don't know what will happen with quantum computers. What we do know is that the field is exciting, the scientific challenges it faces are interesting—and anyone who says they know for sure what the future holds is probably selling you something. ●

FROM OUR ARCHIVES

Errors in the Machine. Zaira Nazario; May 2022. ScientificAmerican.com/archive

MosaiQ is a photonic quantum computer developed by Quandela in France.

Sameer Al-Doumy/AFP/Getty Images



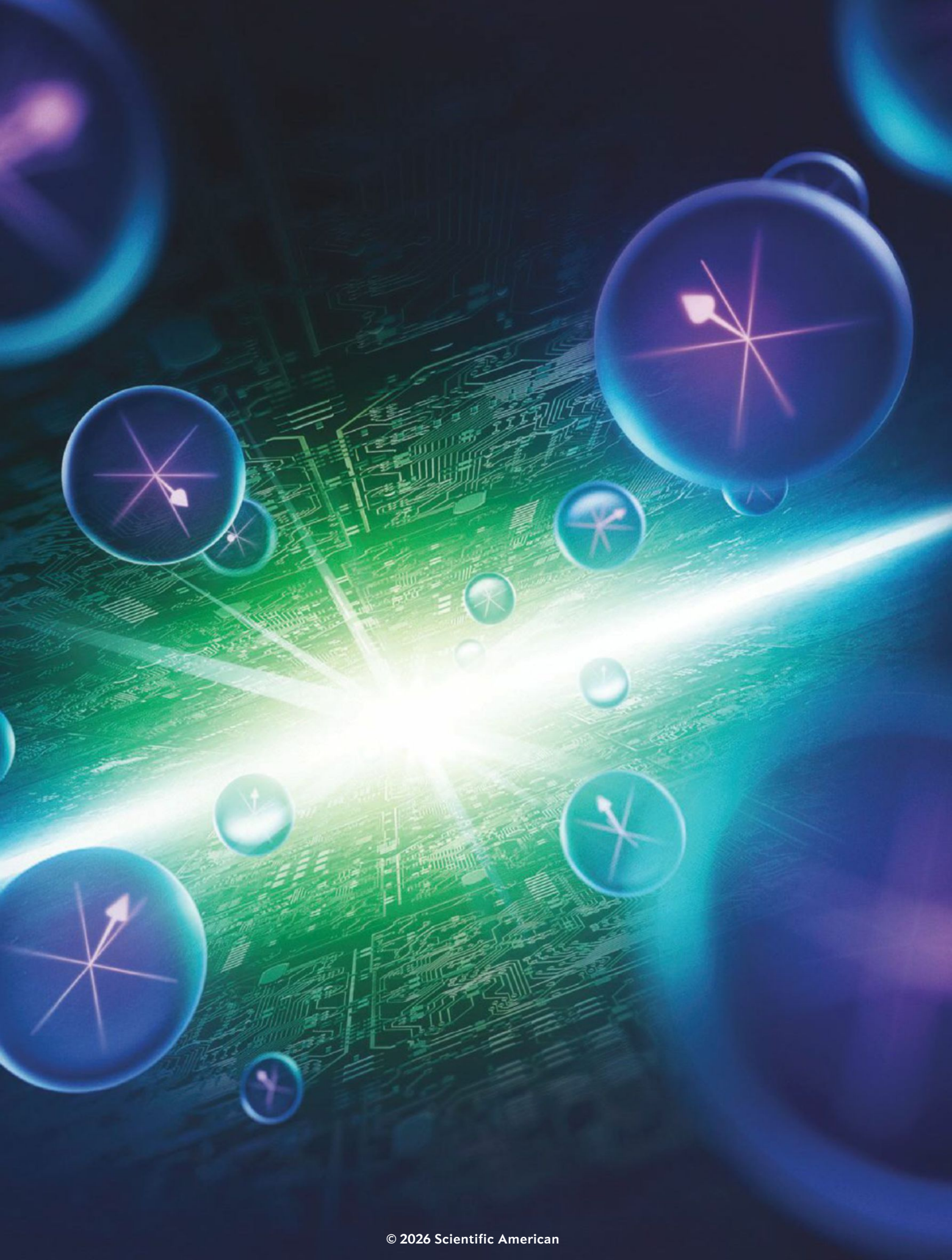
WHAT'S A QUANTUM COMPUTER GOOD FOR, ANYWAY?

Quantum computing promises profound power in cryptography, materials design, telecommunications, and much more. But those dreams won't become reality overnight—if ever

BY ZEEYA MERALI
ILLUSTRATION BY OLENA SHMAHALO

THE 21ST-CENTURY FERVOR about building the first industrial-scale quantum computer, pioneering theoretical physicist Peter Zoller says, is akin to the 20th-century obsession with becoming the first to conquer Mount Everest. "When you're climbing, you look around worrying, 'Who is number one?'" he says. "When you reach the top, that's when you ask yourself, 'Why the hell did we actually do this?'"

In 1995 Zoller and Ignacio Cirac, then a postdoctoral researcher in Zoller's group at the University of Colorado Boulder, proposed the first realistic blueprints for a quantum computer. Their idea was to use trapped ions as "qubits"—the quantum equivalent of digital bits, able to exist in a superposition that simultaneously represents 0, 1 and all positions in between. More than a decade earlier physicists Paul Benioff and Richard Feynman had independently suggested that machines harnessing the quantum realm's weirdness could, in theory, outperform classical computers at some tasks. Today



teams around the world are developing ever bigger quantum processors using qubits made from ions, neutral atoms, superconducting loops, and more. IBM and Berkeley, Calif.–based company Atom Computing currently lead the charge with quantum computers hosting more than 1,000 qubits, and last year a research group at the California Institute of Technology reported that it had built a record-breaking array of more than 6,000 qubits.

"It's an exciting time because people are fielding quantum computers with hundreds and thousands of qubits," says Nobel Prize–winning quantum physicist John Martinis, a professor emeritus at the University of California, Santa Barbara, and co-founder of quantum hardware company Qolab.

In 2019 Google researchers, led by Martinis, reported that their 53-qubit processor, Sycamore, had become the first to achieve "quantum advantage," performing a calculation in 200 seconds that they estimated would take the best classical supercomputers around 10,000 years to solve. That supercomputer number was later disputed—IBM argued that its best classical computer could actually perform the task in just two and half days—but even if it held up, the calculation was of only academic interest as a proof of principle. "Google's 2019 demonstration of quantum [advantage] was an important milestone, but many people would say that it did not yet constitute a breakthrough on a problem of broad practical significance," notes quantum physicist Kihwan Kim, now at the Institute for Basic Science in South Korea.

Experts agree that to tackle useful problems that lie beyond the reach of even the best possible classical supercomputers, we need qubit numbers to jump significantly, potentially to a million or more. In addition, quantum physicists will need to engineer robust qubits that maintain their quantum properties for a longer time, and they'll have to find ways to fix errors introduced during calculations. In March a multi-institutional group of researchers reported that IBM's superconducting Heron processors could accurately predict the results of neutron-scattering experiments that measured the structure of a specific antiferromagnetic crystal to an unprecedented scale, using 50 qubits or fewer; the physicists noted, however, that classical computers could perform the same feat faster and more accurately.

So what will quantum computers really be good for—and when? Experts say we are still years away from quantum computers able to handle practical applications that classical computers cannot, which might include breaking common data-encryption schemes, simulating quantum processes for fundamental physics, and designing better drugs and materials. That said, Martinis—an expert on scaling up quantum hardware—notes there are no guarantees that million-qubit computers will ever be created. "The proof," he says, "will be building them and seeing that they work."

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CRYPTOGRAPHY

THE MOST NOTORIOUS PROMISE of quantum computers has been that they will one day break RSA encryption, a long-standing protocol used worldwide to secure bank transfers, cryptocurrencies and digital communication. That day may come surprisingly soon. It was long thought that cracking encryption would require a processor with at least a million qubits. But in February a team from Iceberg Quantum in Sydney, Australia, dramatically reduced that estimate, calculating that with careful optimization and error correction, hackers might need fewer than 100,000 qubits for the feat. In March, Google announced a new commitment to migrating its systems by 2029 to protect them from quantum hacking.

Although the Iceberg claims have yet to be peer-reviewed, they are credible and have caused a stir, says Artur Ekert, a cryptography expert at the University of Oxford. "Many think that the threat to encryption from quantum computers is just mumbo jumbo—and I have also been skeptical—but it could just take a few more papers like this one to make the notion of breaking RSA relevant," he says. Martinis's opinion has also shifted in recent years. "If you are worried about RSA encryption—as you should be—I would say it might be broken in five to 10 years," he says.

RSA encryption leverages the fact that it's easy to create a secret key by multiplying two large prime numbers together but effectively impossible for any classical computer to determine the key by efficiently factoring it back into those constituent primes. A classical computer could test successive numbers sequentially, remembering each value and looking for a pattern, but this approach is infeasible with large numbers, Ekert explains. Modern classical algorithms use other methods but remain inefficient because the execution time increases exponentially with the size of the number to be factored.

The quantum world, however, is not so constrained. Qubits can take on multiple values simultaneously and become entangled with one another, amplifying their power. "Essentially it can cover all

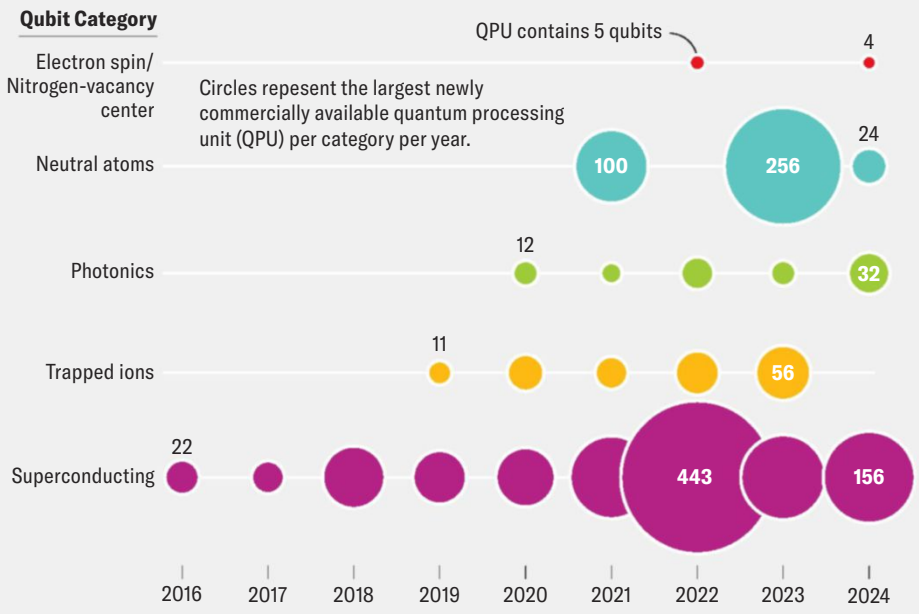
possible computational paths at the same time," Ekert says. In 1994 theoretical computer scientist Peter Shor, now at the Massachusetts Institute of Technology, proposed that a hypothetical quantum computer could use this property to crack RSA encryption. If and when one does, it will probably use the algorithm Shor developed.

There are proposals for quantum-resistant cryptographic algorithms; the U.S. National Institute of Standards and Technology (NIST) published three such schemes in 2024. Zoller thinks such work largely defuses the threat because it suggests the world can move away from RSA encryption before quantum hackers arrive. "Shor's algorithm may ultimately be remembered as a landmark scientific achievement of great historical importance for inspiring the development of quantum computers, as much as for its implications for breaking encryption," he says.

Ekert feels less reassured. Last year, he notes, a computer scientist in China proposed—it turns out incorrectly—a quantum algorithm capable of breaking NIST's top candidate, which is called lattice-based encryption. "It took the brainpower of the whole quantum cryptography community [more than a week] to find a mistake, showing you how close those things are," Ekert says. "Maybe next time it will be correct."

Qubits on the Rise

Qubits—the quantum version of digital bits—are the basis of quantum computing, so one might expect that the more qubits a quantum computer has, the better it must be. But not all qubits are created equal, and they can come in various physical forms. And more qubits can mean more computational errors. Here are year-by-year records for the highest numbers of five major categories of qubits in newly commercially available quantum computers.



Source: *The Quantum Index Report 2025*, by Jonathan Ruane et al.; M.I.T. Initiative on the Digital Economy, Massachusetts Institute of Technology, May 2025 (*data*)

FUNDAMENTAL PHYSICS

One domain where quantum processors are already seeing success is in modeling particle interactions to solve mysteries at the heart of fundamental physics. "It goes back to Feynman, who articulated that you can't really understand how nature works unless you build it at the same length scale," says quantum physicist and material scientist Michelle Simmons, founder and CEO of Silicon Quantum Computing (SQC) in Sydney.

Simulating interactions of multiple particles rapidly becomes impossible with a classical computer, explains Daniel González-Cuadra , a quantum physicist at the Institute for Theoretical Physics in Austria. "The information that it takes to describe the state of these systems grows exponentially with the size of the system, and at some point you just don't have enough memory," he says. Capturing all the complexities requires an equally complex quantum machine.

Groups around the world are making progress on this front. One big area of focus is increasing the "coherence" of qubits so they stay in superposition long enough to carry out their calculations. In 2021 Kim's China-based team demonstrated that trapped-ion qubits can maintain coherence for more than an hour, which he says was "a very important benchmark for scaling up meaningful quantum simulations."

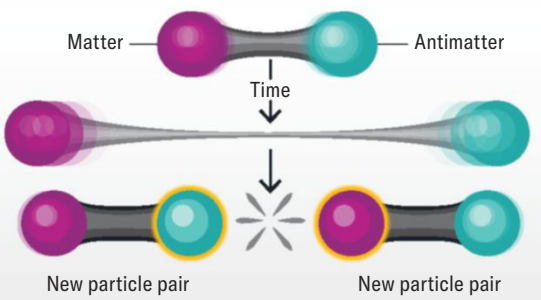
Last year two teams independently published real-time quantum simula-

Graphics by Jen Christiansen

Snappy Simulations

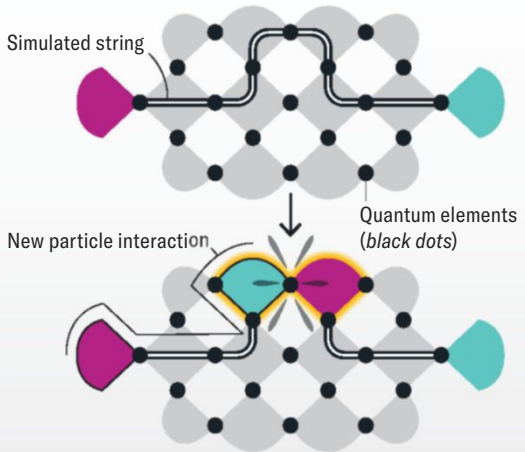
Quantum computers, somewhat unsurprisingly, can be used to simulate quantum physics. In one recent example, from 2025, two independent teams used two very different approaches (*below*) to perform quantum simulations of antimatter-matter particle pairs arising from string breaking. This is a theoretical process (*right*) named for the way interacting particles, when pulled apart, can act as if they are connected by a stretchy string, which breaks with the creation of a particle pair.

String Breaking



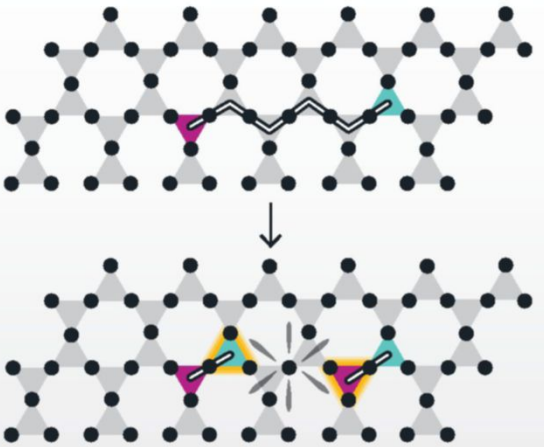
Quantum Simulation 1

Google Quantum AI simulated string breaking on the company's Sycamore chip—which uses superconducting loops as qubits—by building a two-dimensional square lattice of qubits.



Quantum Simulation 2

Instead of using a multipurpose chip such as Sycamore, researchers at the Institute for Theoretical Physics in Austria and QuEra Computing in the U.S. custom-built a quantum string-breaking simulator using a lattice made from rubidium atoms.



tions of the creation of matter and antimatter during a process called string breaking. According to the Standard Model of particle physics, pairs of strongly interacting subatomic particles, such as quarks, behave as though they are joined by an elastic string, "like a violin string that vibrates," explains quantum physicist Pedram Roushan of Google Quantum AI in Santa Barbara. Roushan's team ran its simulation on Google's Sycamore chip, which uses superconducting loops as qubits. The simulation showed how pulling two particles apart increases the string's tension until it finally snaps, releasing the stored energy by generating a new pair of matter and antimatter particles. "These theoretical concepts were known since the 1970s, but we were able to visualize them and take a picture of the strings and their breaking," Roushan says.

The Sycamore experiment was an example of a digital simulation, meaning it was performed on a multipurpose chip with circuits of qubits designed to do many different tasks. In contrast, González-Cuadra, Zoller and their colleagues worked with a team at QuEra Computing in Boston to create an analog simulator—a lattice of neutral-atom qubits specially built to simulate string breaking. The two string-breaking simulations are among the first to model particle interactions in two spatial dimensions, González-Cuadra says. "The physics is richer, so we could see how these strings fluctuate," he explains.

These kinds of simulations won't replace particle physics experiments. Instead they will help physicists hone their theories and make testable predictions that can be checked at particle accelerators. And so far they have simulated only simple models that can also be checked with classical computers. But González-Cuadra believes quantum simulators will start to surpass their classical counterparts in a couple of years, marking an era of true quantum advantage. This possibility raises the question of how physicists can be sure their quantum simulations are spitting out reliable results. To answer it, last year Zoller and his colleagues posted a preprint paper on arXiv.org describing a strategy for developing an analog quantum machine that not only makes predictions but also quantifies the uncertainty in those predictions. "If you ask me what the big challenge for quantum simulation is, it is the frontier of verification," Zoller says.

Source: "Simulation of Matter–Antimatter Creation on Quantum Platforms," by Michele Burrello, in *Nature*, Vol. 642; June 12, 2025 (*reference*)

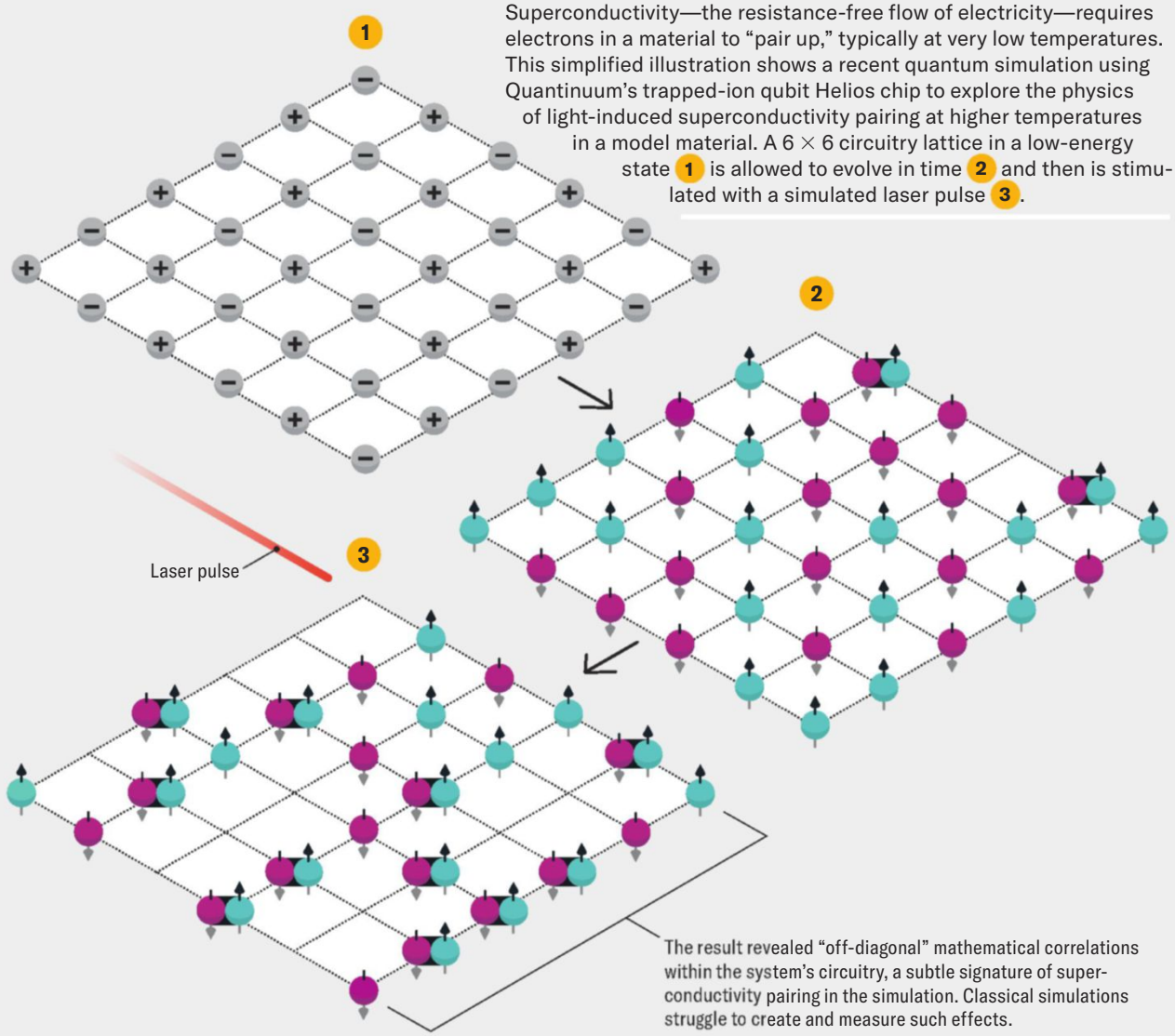
MATERIALS DESIGN

THE DREAM, Zoller says, is for quantum simulators to shift from a passive "discovery mode"—in which they are used to model nature—to an "active design mode" in which quantum computers would spit out recipes for synthesizing new molecular structures with specific desirable properties. The quantum engineering of new molecules could lead to better drugs and to batteries that don't use costly, environmentally damaging commodities such as rare earth elements. "These things take billions of dollars, so if you just make something even a few percent cheaper or a few percent better, then that's really worth it," Martinis says. "It could be a huge thing not just monetarily but for changing how things are built to make them more ecological."

Room-temperature superconductivity is one high-priority target. Superconductivity, the free flow of electricity without resistance, typically requires a material to be cooled to extremely low

Simulating Superconductors

Superconductivity—the resistance-free flow of electricity—requires electrons in a material to "pair up," typically at very low temperatures. This simplified illustration shows a recent quantum simulation using Quantinuum's trapped-ion qubit Helios chip to explore the physics of light-induced superconductivity pairing at higher temperatures in a model material. A 6 × 6 circuitry lattice in a low-energy state 1 is allowed to evolve in time 2 and then is stimulated with a simulated laser pulse 3.



Source: "Superconducting Pairing Correlations on a Trapped-ion Quantum Computer," by Etienne Granet et al.; February 17, 2026 (arXiv:2511.02125v3) (*reference*)

temperatures, which makes it impractical for many applications. But certain materials exhibit the phenomenon at higher temperatures, and some researchers hope quantum engineering can help them find new superconducting materials that don't need any cooling at all. "These systems consist of 10^{23} particles, whereas classically we can model only about 100 particles," says Henrik Dreyer, a quantum physicist at Quantinuum in Munich. Physicists would need to reduce the error rates in quantum processors to just one in a million to make it possible; at the moment the best chips are down to slightly below one in 1,000, Dreyer explains.

> "We can now simulate things like superconductivity, artificial photosynthesis and small drug designs." —MICHELLE SIMMONS
> *SILICON QUANTUM COMPUTING*

Dreyer and his colleagues have been performing digital simulations of cuprate superconductors using Quantinuum's Helios chip, which employs 98 trapped-ion qubits. In carefully controlled laboratory conditions, shooting these materials with a laser can very briefly—and surprisingly—create a superconducting state at a relatively high temperature. "The first question is: Why?" Dreyer says. Last year Quantinuum posted a preprint on arXiv saying its two-dimensional simulation modeling the material shows that under laser fire, its electrons pair up—a condition necessary for flow without resistance. "The ultimate question is," as posed by Dreyer, "Can we engineer it to do this at room temperature for a minute, an hour, 10 days, or more?"

Meanwhile Simmons and her SQC colleagues in Australia have developed a simulation system called Quantum Twins—a 2D array of 15,000 clusters of phosphorus atoms embedded in silicon—to create analogs of various materials. In February the team reported that the platform can simulate the transition between insulating behavior and metallic conduction. "We can now start to simulate things like superconductivity, different battery materials, artificial photosynthesis and small drug designs," Simmons says.

Google Quantum AI's Sergio Boixo notes that the company has collaborated with BASF on battery design, Sandia National Laboratories in Albuquerque on fusion energy, and German chemical company Covestro on pharmaceutical development. Last year it implemented an algorithm for modeling molecular structure on Willow, Google's 105-qubit superconducting processor, that can be used in combination with nuclear magnetic spectroscopy. The technique, which works by bouncing signals onto qubits and effectively listening for their echoes, runs 13,000 times faster on Willow than an equivalent algorithm would on the best classical supercomputer. One important aspect of the algorithm's design is that it allows results to be corroborated by another quantum machine. "Quantum Echoes is the world's first quantum-verifiable algorithm with quantum advantage," Boixo says. "We're optimistic that we're going to see the first practical applications in five years."

QUANTUM AI

If you really want to generate hype, combine the word "quantum" with "AI," jokes Jacob Biamonte, an expert on quantum machine learning at ÉTS Montreal. Indeed, as quantum processors get bigger, some physicists are focusing on using them to boost the performance and energy efficiency of classical artificial intelligence.

Last year SQC launched Watermelon, a quantum-enhanced AI processor, to help speed up machine learning. Classical AI systems are already adept at finding patterns in vast datasets, which makes them particularly useful for optimizing communications and energy networks, for instance. SQC's quantum technique builds on classical reservoir computing, a method for taking input data points and transforming them onto a higher-dimensional neural network, making it easier to find patterns. In 2017 scientists in Japan predicted that the classical nodes of the neural network could be replaced by a smaller number of qubits subject to quantum interference. "The advantage of having a quantum reservoir is that you get an exponential increase in dimensionality," Simmons says, enabling a quantum reservoir to achieve the same training results as a classical reservoir but potentially faster and using fewer resources.

Watermelon's first commercial trial—in collaboration with Australian telecommunications company Telstra—has shown promising results. Telstra already uses AI to monitor latency and bandwidth patterns on its networks. It takes about three weeks to train the company's models using standard clas-

sical methods. With Watermelon's help, Telstra achieved the same training results in just two days. "In the grand scheme of the world, that is quite significant because at the moment, data centers are very power hungry," Simmons says, noting that similar optimizations could be rapidly rolled out to other energy-intensive tasks, such as training AIs for image recognition, fraud detection and market prediction. "I feel like I'm in this freight train that's going at superhigh speeds," she says.

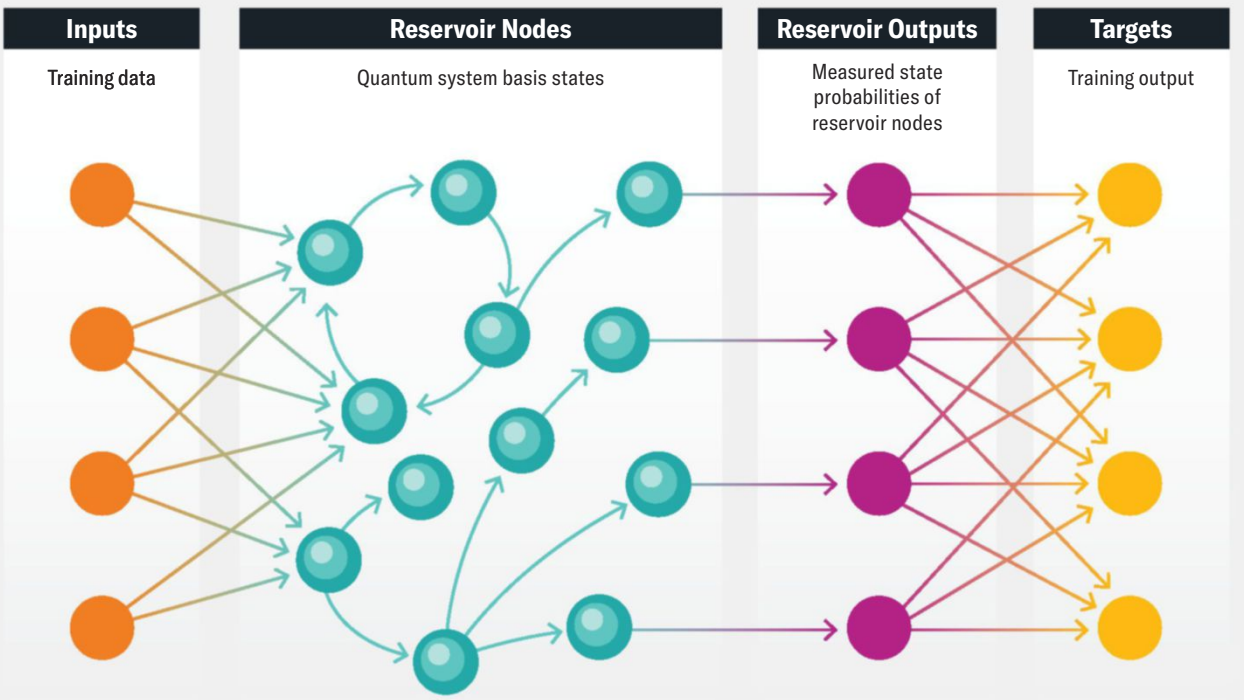
Ekert, however, remains cautious about the longer-term benefits of using quantum AI processors to analyze classical datasets. "Turning classical data into a quantum form is terribly inefficient," he says. Where quantum computing and machine learning are already being combined most helpfully, Ekert argues, is in physicists' use of classical AI to design quantum error-correcting codes and better quantum hardware. Last year, for example, Finnish company QMill launched a classical AI service for compressing quantum circuits, reducing the number of gates needed for operation by 20 to 50 percent. Biamonte also thinks the current vision is too small. "If the goal is to use quantum computers to do machine learning for classical data, it doesn't even make sense, because classical machine learning is already so good," he says.

> "We're optimistic that we're going to see the first practical applications in five years." —SERGIO BOIXO *GOOGLE QUANTUM AI*

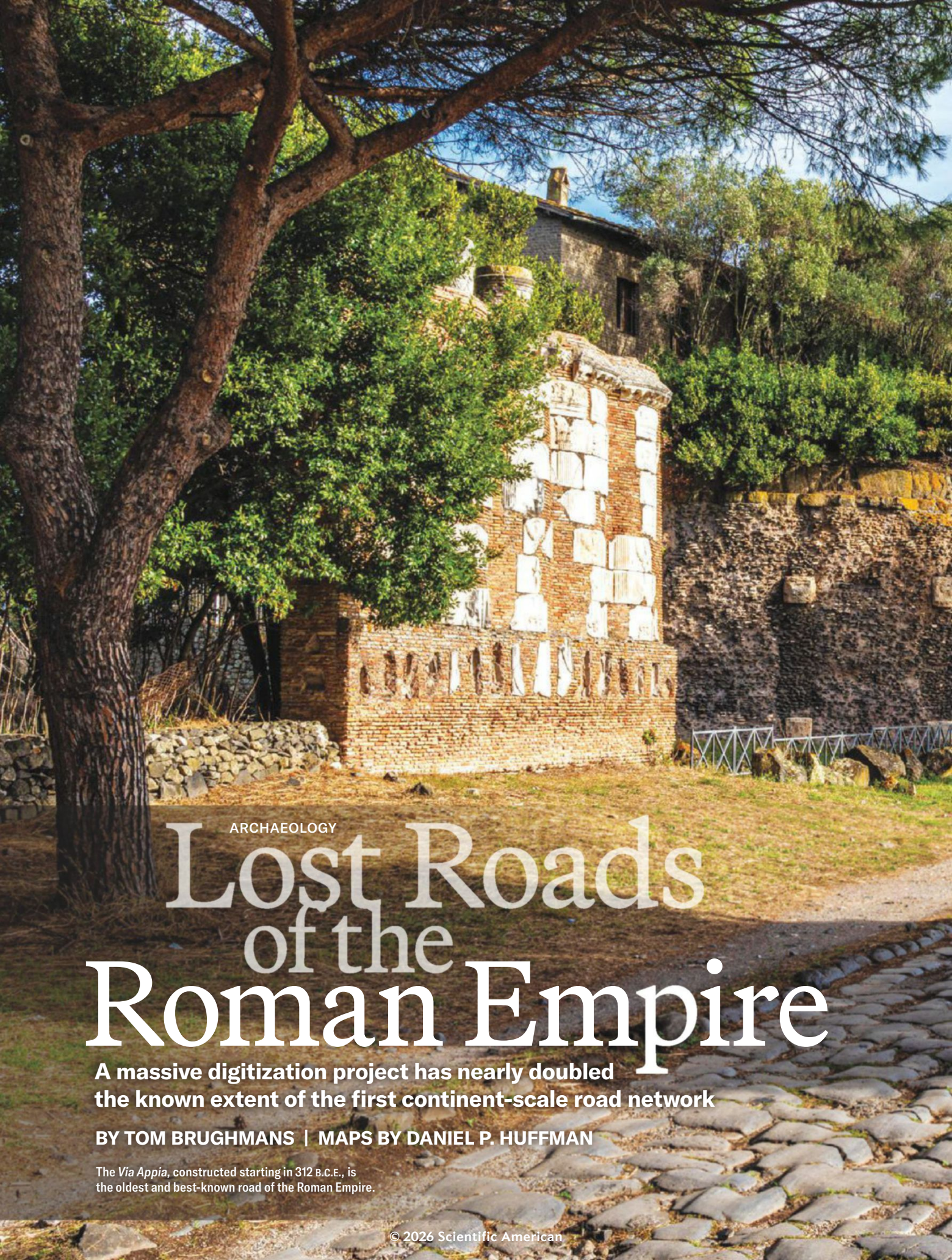
If quantum processors could one day be used to analyze quantum data directly, however, that would be a game changer. "There should be these wonderful patterns that classical computers cannot detect because there are just too many data for their memory," Biamonte says. A quantum AI could riff on the molecular structure of an existing patented drug, for instance, to generate multiple different configurations with the same benefits. It could then assess those molecules to see whether they could be synthesized and patented before a company committed funds to trying to make them. "That's the exciting future that doesn't exist yet," Biamonte says. ●

A Quantum AI Reservoir

Reservoir computing is a classical machine-learning technique that maps training data onto nodes of a higher-dimensional neural network to aid pattern recognition. Computer scientists have shown how a quantum reservoir, in which the neural network's nodes are replaced with interacting qubits, can access vastly greater numbers of states. This could allow AI systems to be trained faster and with fewer resources than in classical approaches. This simplified diagram illustrates the concept.



Source: "Quantum Reservoir Computing Implementation on Coherently Coupled Quantum Oscillators," by Julien Dudas et al., in *npj Quantum Information*, Vol. 9; July 7, 2023 (*reference*)



ARCHAEOLOGY

Lost Roads of the Roman Empire

A massive digitization project has nearly doubled the known extent of the first continent-scale road network

BY TOM BRUGHMANS | MAPS BY DANIEL P. HUFFMAN

The *Via Appia*, constructed starting in 312 B.C.E., is the oldest and best-known road of the Roman Empire.

ON A RECENT VISIT to Rome I walked along the *Via Appia* (also called the Appian Way), past the presumed house of Stoic philosopher Seneca, and felt transported in time. Constructed starting in 312 B.C.E. to carry troops southeast toward Capua and, eventually, the port city of Brindisi in the heel of Italy's boot, the *Via Appia* is the oldest and best-known road of the Roman Empire.

Scholars have long regarded it as the quintessential Roman road: a straight highway extending as far as the eye can see, paved with slabs of volcanic stone, lined with pointy cypress trees and, of course, connecting to Rome. It is amazing to know that Romans walked here more than 2,300 years ago. No wonder this marvel of ancient engineering—long stretches of which remain remarkably intact today—is known as the Queen of Long-Distance Roads.

But iconic as it is, the *Via Appia* is not the archetype researchers have assumed it to be. My colleagues and I have produced a new map of Roman roads that, for the first time, reveals their locations at high resolution in a single, open resource. What we found revolutionized our view of the road system that undergirded this superpower of the ancient world.

Historians and archaeologists have been studying Roman roads for centuries. In that time, they have found remnants of the roads themselves, crumbling milestones, and historical texts about major connections between settlements. But efforts to plot the roads based on these piecemeal sources yielded a low-resolution map of the Empire with approximate locations rather than precise ones.

Knowing the location of Roman roads matters for understanding how the Empire conquered and pacified new territories and transported food to keep its people alive. Their development meant that for the first time in history, an area the size of the European Union was covered by a network that allowed the flow of people, goods, ideas and disease from Egypt to Germany, Spain to Turkey. To that end, my team and I set out to build the first high-resolution digital map of the Empire's roads, combining information from historical datasets with modern topographical maps and satellite data, among other sources. We expected that 200 years' worth of research tradition would allow us to simply connect the data points our predecessors had collected. We were wrong.

Our research implies that in the second century C.E., the period when the Empire had its maximum extent, this road network comprised some 300,000 kilometers—nearly double the previously known total length of Roman roads. This is a massive discovery. It's also very humbling because despite seeing the full scope of the network, we know the precise location of only 2.7 percent of it. (The preserved sections of the *Via Appia* are part of this well-known minority.) How, after centuries of research, can we know so little about this system? And where are the lost roads of the Roman Empire?

LET'S START WITH WHAT WE DO KNOW. The ancient Romans invented far fewer things than they are often credited for, and they certainly did not invent the road. Rome's strength lay in its ability to recognize a good idea and scale it to the size of a continent.

The generals and emperors of Rome conquered regions that already possessed elaborate road systems connecting densely urbanized areas. In the east, the Hellenistic kings who succeeded Alexander the Great had built many cities, such as Antiochia, and connected them with roads just as the Persians, Assyrians and Babylonians had done before them. The Achaemenid Persians even built a "highway" between their capital in Persia, Susa, and Sardis in western Turkey, known as the Royal Road.

The Romans' real innovation was the integration of these disparate local road systems into the first continent-scale road network in human history. And contrary to the proverb, they didn't all just lead to Rome. Massive infrastructure projects purposely linked up the roads of different provinces into a connected whole, unlocking access to far-flung regions from the Atlas Mountains in Morocco to the Danube delta.

For instance, Roman emperor Trajan's takeover of the Nabataean kingdom, centered in what is now Jordan, moved the Empire's frontier to the

Tom Brughmans is an associate professor of classical archaeology at Aarhus University in Denmark. His research focuses on studying material culture to understand how people in the Roman Empire were connected. Brughmans is co-director of https://itiner-e.org

Stefano Valeri/Alamy (*preceding pages*)

Built to transport the Roman army south to expand the Empire's influence, the *Via Appia*, a portion of which is shown here, connected Rome to Brindisi on the Adriatic coast.

Arabian Desert. His legions built the road known as the *Via Nova Traiana,* which ran from the Red Sea port of Aqaba to Bosra in Syria. This major Roman road does not lead to Rome. It was crucial infrastructure for the defense of the Empire and the mobility of its soldiers, connecting several eastern provinces. It formed part of the *Limes Arabicus,* a massive, 1,500-kilometer desert frontier with forts, which dwarfed Hadrian's wall, the 117-kilometer frontier in Britain.

Much of what scholars have pieced together about such infrastructure projects comes from milestones. Like the mile markers along modern highways, these engraved stones informed travelers of their location and distance. The earliest known Roman milestone comes from Sicily and was erected by the consul C. Aurelius Cotta (who was consul in 252 and 248 B.C.E.) following the Roman victory over Carthage in the first Punic War. The Romans implemented this system across the entire Empire.

Milestones were more than just navigational aids: they were propaganda, often inscribed with the name of the emperor or local magistrates who funded the construction or renovation. In Spain, for instance, Augustus, the first Roman emperor, ordered the construction of the *Via Augusta,* a massive arterial route stretching from Cádiz in the south to the Pyrenees Mountains in the north. His name could be read on milestones dotting the entire stretch. The road plugged the people and economy of the Iberian Peninsula more tightly into the rest of the Empire.

For our team, these milestones provided a crucial puzzle piece to our effort to locate missing Roman roads. The word "mile" comes from the Latin *mille passus,* which means 1,000 paces, the length of a Roman mile. A Roman pace was five Roman feet, so the Roman mile was 5,000 Roman feet and equaled about 0.92 of a modern English statute mile, or 1.48 kilometers. In our work milestones served as ancient GPS markers. For example, in the Middle East the discovery of two specific milestones was instrumental in identifying how a Roman road climbed from the Sea of Galilee to the plateau above.

The practice of cataloging inscriptions on milestones is more than a century old. Our breakthrough came from a more recent revolution in the field of archaeology: digitization. By aggregating

New View of an Ancient Network

In developing our digital atlas of Roman roads, we found 8,000 kilometers of roads whose location we know with certainty and 292,000 kilometers of roads that rely on varying degrees of conjecture. We created a confidence map that describes variation in the reliability of our sources and the accuracy of our digitization. It offers archaeologists a detailed guide to where to search for Roman roads.

The *Arc de Berá*, a Roman monument, was built in 13 B.C.E. along the *Via Augusta* in the Catalonia region of Spain. Today it overlooks the N-340, one of many modern European roads that have been constructed where Roman roads once stood.

RichSTOCK/Alamy

databases that include more than 8,000 milestone locations and 14,000 ancient places, we were finally able to play a continent-scale game of connect the dots.

BUT CONNECTING THE DOTS WITH CERtainty is possible only if you can see the lines. And for the vast majority of the Roman network, those lines have vanished. We had to do a lot of detective work to reveal them.

Samosata, in present-day southeastern Turkey, was the capital of the kingdom of Commagene until it was incorporated into the Roman Empire in the first century C.E. We wanted to find its roads. Sadly, people can no longer visit this ancient city, because it was submerged under dozens of meters of water after construction of the Atatürk Dam on the Euphrates River in the 1980s. The dam inundated Samosata, along with an area of more than 800 square kilometers (equivalent to some 112,000 soccer fields). But cold war–era satellite photography aided our search. We were able to find traces of ancient roads in these declassified images, which were taken before the reservoir was flooded.

It's not just dams that led to the destruction of roads. Population growth in a region requires the development of plots of lands for housing. Digging foundations destroys traces of past human activity, and it is not always possible to excavate before destruction. In these situations, historical satellite photography can act as a kind of time machine that allows us to examine a landscape as it was before urbanization. In the images, we can see traces of roads long since destroyed—true lost Roman roads.

Historical satellite photography is not our only tool for peering into the past. Detailed topographic maps—a common by-product of wars—can also reveal landscapes as they looked before extensive development. For instance, France controlled Syria and Lebanon between the two world wars, and its army created detailed maps of these territories in that period. On the interbellum-era French military maps, we can clearly see a line labeled as a Roman road in Bosra in Syria, that is now partly covered by suburban development.

These detailed landscape sources also allowed us to map the roads more precisely by taking the topography into account. The previous reference

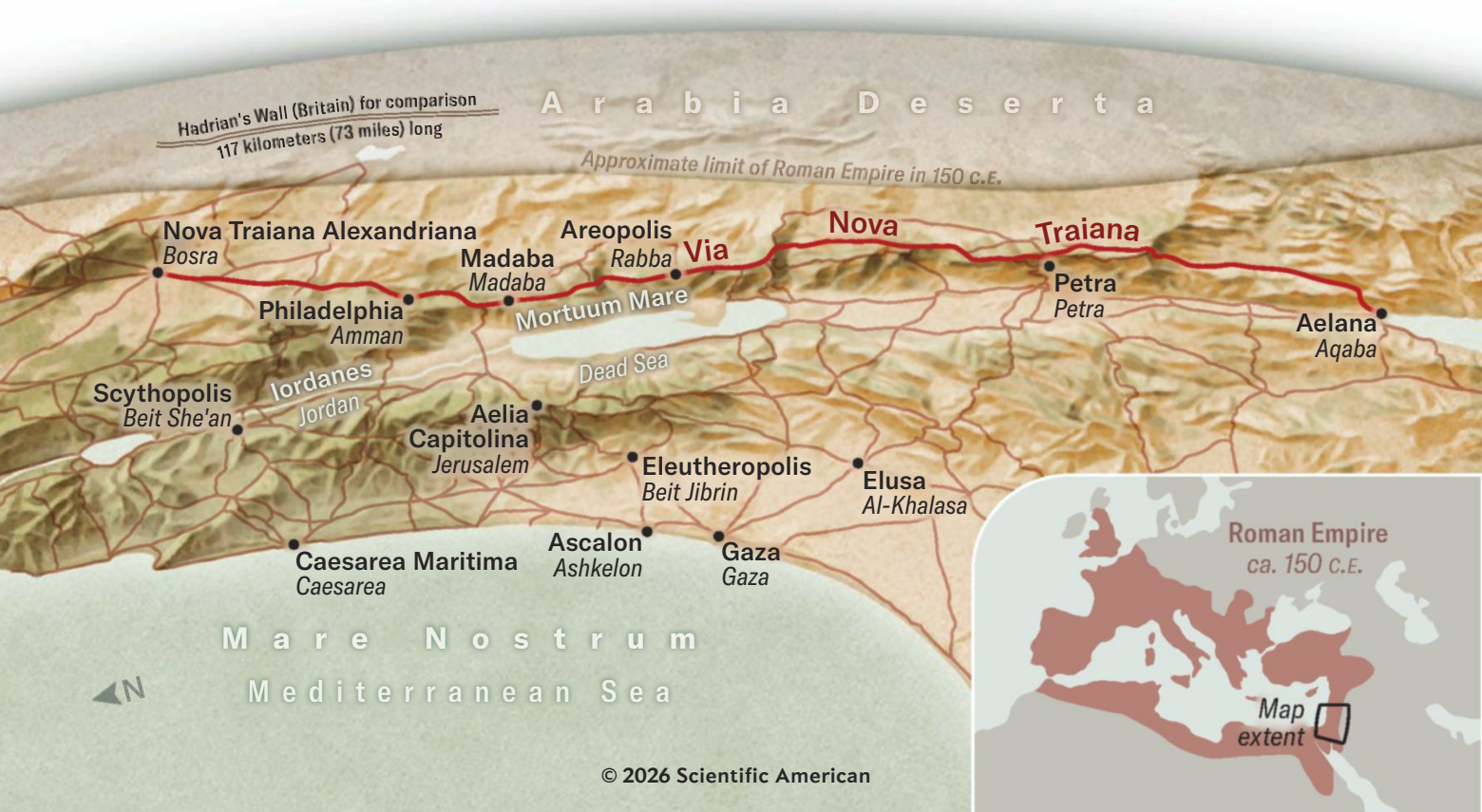
The province of Baetica in Spain was a hub for the production of olive oil, which was vital to the success of the Roman army. Archaeologists know the exact locations of many structures and settlements in the region (*small black dots*) but not the roads that must have connected them.

work for the entire Roman Empire was the *Barrington Atlas of the Greek and Roman World,* published 25 years ago. This mammoth work was foundational for creating an integrated picture of roads and places in the ancient world. It was subsequently digitized and remains the only such resource for the Empire as a whole. But its maps are at 1:500,000 or 1:1,000,000 scale—that is, one inch on the map would reflect 7.89 miles or 15.78 miles on the ground, respectively—resulting in roads that do not conform to the shapes of the landscape.

In this atlas, a mountain stands between the ancient Greek cities of Mantinea and Argos near Mycenae on the Peloponnese Peninsula. A 62-kilometer-long road winds around the mountain, a route it would take roughly 20 hours to walk. Ancient hikers had another option, though: cross the mountain passes, which cut the trip down to 14 hours. We mapped the sharp switchbacks that characterize such mountain hikes. A map this detailed shows lots of zigzags, which is one of the reasons we ended up extending the Roman road network by a staggering 111,000 kilometers. We can be certain that 300,000 kilometers is much closer to its actual length, considering the complexities of the terrain.

In addition to consulting historical satellite photography and topographical maps, we used the tools of paleogeography—the reconstruction of ancient landscapes through studies of their sediment profiles, among other factors—to guide our search for Roman roads. We know that landscapes changed significantly in the deltas of the region's major rivers. The Rhine and Meuse Rivers merged in the southern Netherlands into a historically transforming landscape of wetlands, marshes and islands as the rivers changed their courses. The Dutch famously canalized much of their country, including large sections of the rivers, even turning their ability to control the flooding of riverine wetlands into a weapon against Spanish invaders in the 17th century. This history also means the delta landscape we see today bears little resemblance to the situation 2,000 years ago. The Dutch members of our team turned to existing reconstructions of the riverine landscape as it was in Roman times to identify old, abandoned riverbeds and thus locate the dry land between settlements that could have supported roads.

WE CAN BE CERTAIN of road locations only if parts of the path have been excavated or are still visible in the landscape, as is the case for the *Via Appia*. Archaeologists have excavated sections of roads all over the Roman Empire's territory and surveyed expansive landscapes in search of such traces. But excavation is expensive and time-consuming. It is usually carried out as a direct reaction to development and



Not all major Roman roads lead to Rome. The *Via Nova Traiana* ran from the Red Sea port of Aqaba to Bosra in Syria. It formed part of a massive desert frontier with forts.

tends to focus on point locations such as villas or milestones. Excavating a long linear feature over vast landscapes is simply not easily done. For this reason, we know much more about the settlements and farms where the Romans lived than we do about the roads that connected them.

Take the province of Baetica in the south of Spain, for instance. It was crucial for the success of the Roman legions. Huge surpluses of olive oil were produced in the Guadalquivir river valley there. Olives were transported over roads from the groves to the presses where their oil was extracted and bottled into enormous, globular ceramic amphora containers, which were then shipped down the river and across the seas to the Roman army as far afield as Germany. This part of the Empire was densely occupied, and we know the locations of hundreds of farms, presses, ceramic kilns, river ports and settlements. But zooming into our map reveals that some of these landlocked places were not connected by a known road. There are many such places throughout the Empire that must have been connected by roads of some form or other for their inhabitants to reach their homes or olive groves.

We found 8,000 kilometers of roads for which we know the location with certainty. That's roughly the distance of a drive from Paris to New Delhi over modern roads. The remaining 292,000 kilometers (equivalent to seven times the circumference of Earth) of roads on our map rely on varying degrees of conjecture. We may have ancient written sources indicating there was a Roman road in a particular region, for example, but limited information about where in the landscape it ran.

As researchers, we must be open and explicit about what is observed and what is informed conjecture. That is why we created a confidence map that describes variation in the reliability of our sources and the accuracy of our digitization. It essentially charts our ignorance. This approach gives archaeologists the first detailed guide to where future searches for Roman roads are likely to reap the greatest rewards.

Tens of thousands of kilometers of roads remain to be discovered. Our publicly available online atlas, called Itiner-e, reveals where to look for them. And it is working. Since its launch, we have received pointers from around the globe to help us find these lost thoroughfares of the Roman Empire. The search is on for the roads that changed the world. ●

FROM OUR ARCHIVES

Pompeii Time Capsule Reveals Secrets to Durable Ancient Roman Cement. Humberto Basilio; ScientificAmerican.com, December 9, 2025. ScientificAmerican.com/archive

The Romans used milestones, such as this one on the *Via Domitia* in Herault, France, across the Empire to inform travelers of their location and distance. These stone markers can be used to reconstruct the paths of Roman roads.

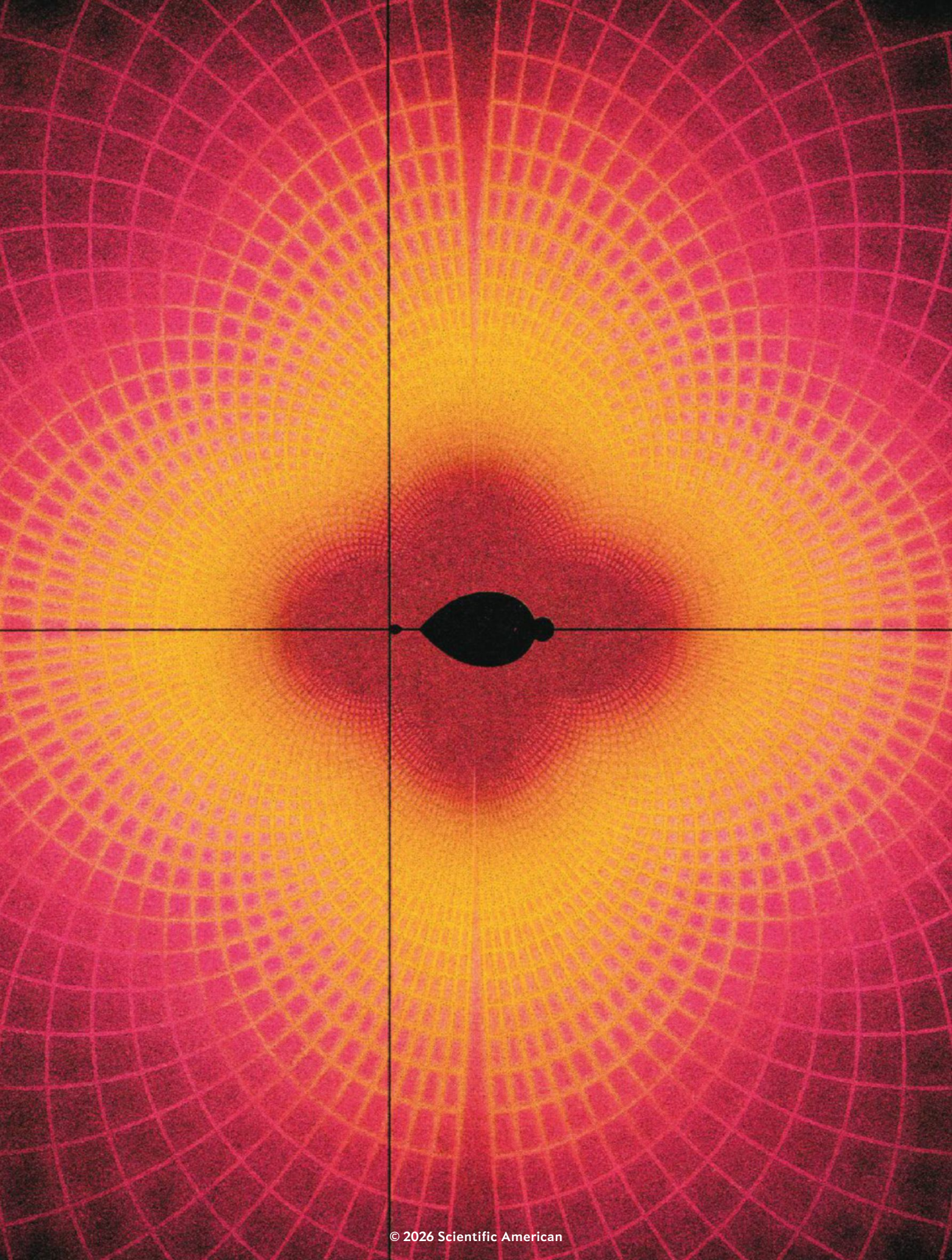
Hemis/Alamy

The Scariest Problem in Math

The most important unsolved mystery in mathematics is nearly 170 years old, and there's a million-dollar reward for its solution. Why is hardly anyone trying to find it?

BY JOSEPH HOWLETT
ILLUSTRATIONS BY DTAN STUDIO

Bernhard Riemann's hypothesis guesses at some values of a gnarly math function. Proving it would unlock vast, as yet impregnable mathematical realms.



IN OCTOBER 2024 I ATTENDED A WORKSHOP AT HARVARD UNIVERSITY where mathematicians talked through the uses of artificial intelligence in their field. Most were less worried about the future of math than excited about a new tool they might use. During one coffee break, I found myself in a group of participants who all agreed that it made no difference whether a human or a computer solved their favorite open problem. They just wanted to read the proof.

"So you really don't care whether the Riemann hypothesis gets solved by a human or AI?" I asked. I thought I clocked a slight chill, exchanged smirks, knowing looks. It's not unusual for me to feel a step behind in these circles.

"An AI that can prove the Riemann hypothesis is not one I'd want to meet," said Andrew Sutherland, a number theorist at the Massachusetts Institute of Technology. "If that happens, mathematicians having jobs will be the least of our problems."

I'd merely been tossing out the name of an open question I'd heard of. But I began to wonder: What is this math puzzle that is so complicated only a truly formidable superintelligence could resolve it?

Ever since it was first published, in 1859, Bernhard Riemann's conjecture about prime numbers has made every list of the most important unsolved mysteries in mathematics. In 1900 mathematician David Hilbert drafted a list of problems to be solved as a blueprint for 20th-century math, and one of them was Riemann's hypothesis. But at the end of that century the still-open question warranted another wanted poster. In 2000 the Clay Mathematics Institute promised a million-dollar bounty to anyone who solved the Riemann hypothesis, making it one of its seven "Millennium Problems"—the 21st century's own aspirational to-do list.

The Riemann hypothesis is a claim about a mathematical function so gnarly that for most numbers fed as its inputs, no one knows its exact output. Mathematicians are particularly interested in which numbers will lead to the value of this function being zero. Knowing these inputs would essentially give number theorists superpowers. In an instant they'd gain an unprecedented command of their rawest material, the prime numbers. They would be able to say precisely where all the prime numbers lie along the infinite number line. Turning the hypothesis into a theorem would have sweeping consequences across mathematics, including the math behind cryptography and even nuclear physics.

Yet despite the handsome heap of rewards stacked behind it, progress toward the Riemann hypothesis is scarce. There's no news to share. "The basic status is: nothing is happening, and I don't really expect anything to happen," says Alex Kontorovich, a mathematician at Rutgers University. Hardly anyone in the field is even working on it. "I don't spend too much of my day really thinking about it," says James Maynard, a mathematician at the University of Oxford. "I just don't really have any good idea of how to get started."

Why?

THE RIEMANN HYPOTHESIS has assumed such a central place in mathematics because of the exalted status of prime numbers. "Asking me why number theorists care so much about prime numbers is kind of like asking why physicists care so

Joseph Howlett
is a staff reporter for *Scientific American*.

much about forces," says Brian Conrad, a mathematician at Stanford University, perhaps with a tinge of offense.

This obsession goes back thousands of years, to the beginnings of math itself—which, of course, started with counting. The ancient Greeks, for example, held whole numbers as paramount. They studied how to combine them to produce other quantities. You can construct a set of 15 stones by counting three at a time, for instance. But some numbers can't be built this way—there's no way to get 17 stones without counting out each one.

These "prime" numbers, the Greeks realized, are primordial, atomic, fundamental. You can build any number that isn't prime by multiplying a unique combination of primes together, called its "prime factorization." Around 300 B.C.E. Euclid proved that there are infinitely many of these building blocks along the number line. But no one could figure out why they are where they are. "On the one hand, this sounds totally bizarre—primes just are what they are. You're either a prime, or you're not," Maynard says. "But one of the best ways to understand prime numbers is often to think about them as being these somewhat random objects."

So mathematicians became fixated on looking for meaning amid this randomness. During the Enlightenment they constructed vast tables of numbers and their prime factorizations, computing them as high as they could using tedious, handwritten algorithms. To a teenager named Carl Friedrich Gauss, studying these tables became a pastime in the late 1700s. In them he found an order that had eluded mathematicians for millennia.

Between 0 and 100 there are 25 primes. But between 1,000 and 1,100 there are only 16. As numbers get higher, fewer of them are prime. This relation makes sense: the number 17 has only 16 smaller options to be divided by, whereas 117 has 100 more to avoid—it's "harder" for it to be prime.

Gauss obsessively compared the numbers of primes in different intervals, going as high as three million. He observed that this drop-off continued and became more predictable as the numbers got higher. Poring over his tables, Gauss eventually scrawled out an equation for the trend. It predicted roughly how many primes you'd find the higher on the number line you searched.

He eventually moved on to more austere and abstract fixations spanning all of math and statistics. In an 1801 treatise Gauss augmented the primes' power even further, showing they were the key to performing calculations in strange but essential finite number systems. But he never figured out how to prove his initial guess about where the primes lived. In the mid-1800s that effort fell to his mathematical disciple, a young theology student at the University of Göttingen in Germany named Bernhard Riemann, whom Gauss won over with his lectures and trained in the way of numbers.

RIEMANN, A LAPSED THEOLOGIAN, balked at the primes' apparent randomness and sought meaning in them. This quest led him to imagine an impossible-seeming mathematical machine that could nail down the precise location of every single prime in existence. It would walk along the real-number line, picking out the primes and skipping the rest. The workings of this magical machine, he found, could be inscribed in a function that came to be called the Riemann zeta function. The zeta function takes as its input a complex number, the sum of a real number plus an "imaginary" component—a coefficient multiplied by the square root of –1, called i.

Mathematicians picture the Riemann zeta function by using the "complex" plane, with real and imaginary axes. Every complex number is a point on this plane, with its x and y coordinates signifying the size of its real and imaginary parts. Put that number into the Riemann zeta function and work out the resulting complicated equation, and you'll get its output: a different complex number. So the zeta function gives one complex value for every point on the plane. And at some special points on the plane, its value is zero.

"An AI that can prove the Riemann hypothesis is not one I'd want to meet."
—ANDREW SUTHERLAND *M.I.T.*

Riemann realized that the locations of these zeros were key to building his machine. He started with a rudimentary prototype of it—Gauss's guess for the frequency of the primes, which tells you roughly how many primes fall in any interval of the number line. But the true primes' locations didn't match this prediction exactly. (Later mathematicians would prove Gauss's guess by using ideas introduced by Riemann.) Rather they were scattered around it.

But this seemingly random scatter, this leftover error in Gauss's prototype machine, could be described with the zeros of the zeta function. Specifically, the scattering could be broken into an infinite

number of distinct, interacting pieces, the way a musical note can be decomposed into harmonics. Each zero determines one of these harmonics. Its imaginary part determines the harmonic's frequency, its real part the harmonic's strength—how loudly that note is played. Each of these harmonics can be added to Gauss's machine to bring it closer to the perfect one Riemann sought.

The Riemann hypothesis has proved to be a font of surprising connections all over math and beyond to the physical world.

Finding every zero of the zeta function—determining the pitch and volume of every instrument in this prime symphony—would tell you the precise locations of all the primes, fully revealing their rich music. But Riemann knew this solution was out of reach. The behavior of the zeta function was as mysterious as the primes themselves. Still, anything he could say definitively about its zeros would be an enormous constraint on the primes, more than mathematicians had ever known.

In his 1859 paper on the hypothetical machine, Riemann made a guess. The real parts of every zero, he declared, were all the same: ½. They differed only in how imaginary they were. This attribute placed them all along a single vertical line on the complex plane, the line that intersects the x-axis at ½. The first such point, Riemann had surmised, was at 14.13. The next was at 21.02.

The paper cemented the Riemann hypothesis: every one of the Riemann zeta function's zeros falls on this "critical" line, with a real part of exactly ½. The conjecture vastly simplified the music of the primes. Without it the primes were like a conductorless symphony, with innumerable pitches being sounded by instruments at different volumes. "The Riemann hypothesis says all these different instruments in the orchestra of the primes play at exactly the same volume," Kontorovich says.

AT THIS POINT you might be wondering why this strange function on the complex plane is so intertwined with the building blocks of whole numbers and why their relation parallels musical harmonics. If so, you're experiencing just a sliver of the wonder mathematicians feel when they reflect on the Riemann hypothesis. Mathematicians thrive on surprising connections. These links are clues that alert them to something deeper under the surface. Lauren Williams, a mathematician at Harvard University, recently told me that her research is most exciting "when I discover that two mathematical objects that had no reason to be related to each other actually are. Then it's kind of a mystery to try to figure out why and how they're related."

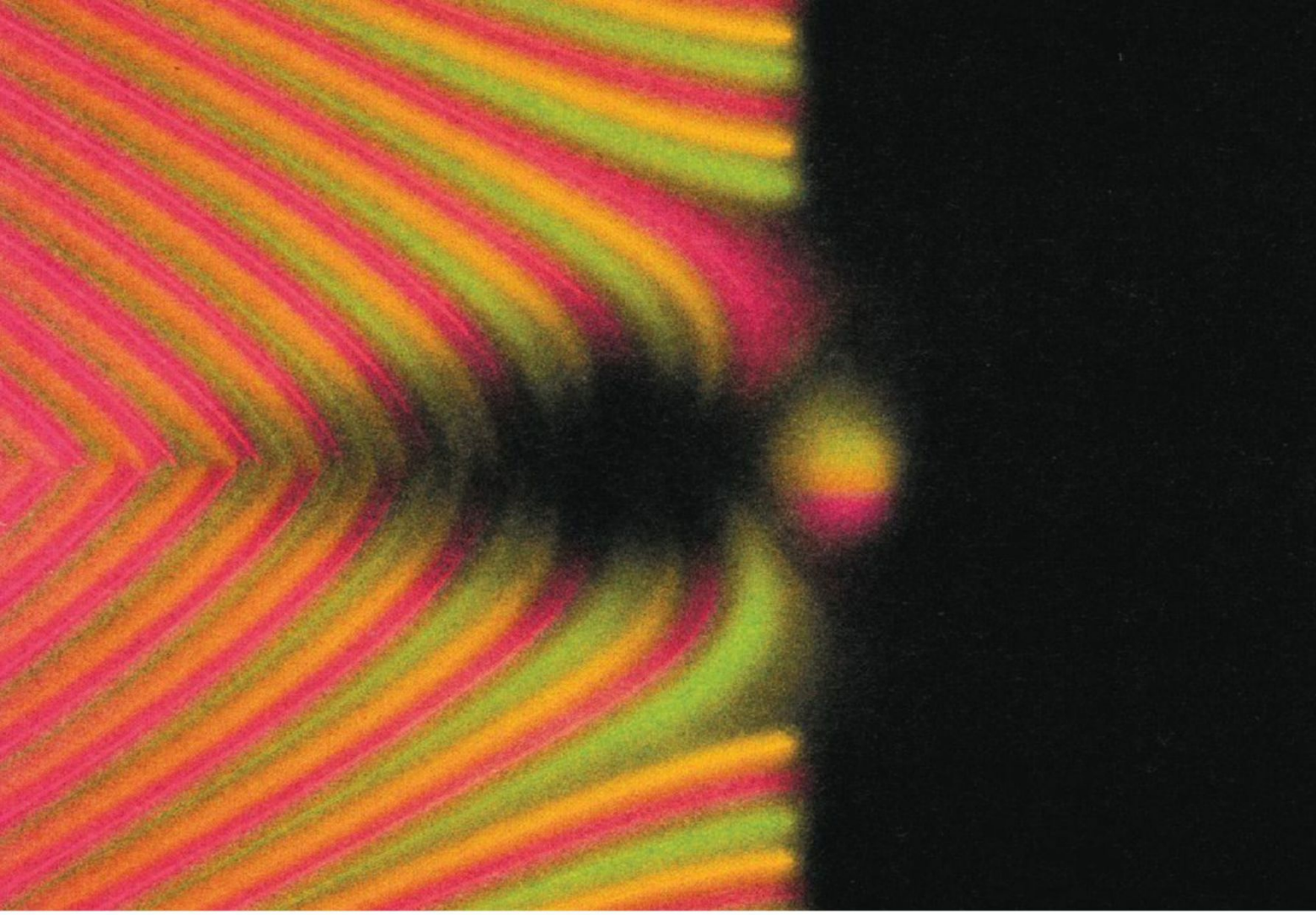
The Riemann hypothesis has proved to be a font of surprising connections all over math and beyond it, to the realm of the physical world. In 1972 physicist Freeman Dyson of the Institute for Advanced Study in Princeton, N.J., happened to have tea with a mathematician who'd noticed strange patterns in the statistics of the zeta function. Dyson immediately recognized the patterns—they matched the theory he'd worked out for the energy levels of atomic nuclei. He unexpectedly helped to solve a problem in pure math, but to this day the origin of the connection remains totally obscure. The Riemann hypothesis has since shown up in the random motion of particles, chaos theory and even the theory of black holes.

Mathematicians haven't waited for a proof to wield the Riemann hypothesis's immense power. "There are hundreds of papers that prove 'x is true if RH holds,'" Kontorovich says. "We've already been assuming it was true for a long time." Using this hypothesis as a starting point greatly broadens what a mathematician can do when it comes to the primes. Their music goes from chaotic to ordered—suddenly the only things missing are the zeros' imaginary parts.

In fact, the Riemann hypothesis has inspired an entire swath of analogies that mathematicians have run with. All kinds of mathematical objects, from simple equations to high-dimensional shapes, have associated "L-functions" that describe some of their properties in the way the zeta function describes the primes. And each L-function has a special critical line like the zeta's $x = ½$: if its zeros lie on this line, then the object it describes makes far more sense.

Mathematicians have taken Riemann's lead, postulating "generalized Riemann hypotheses." If all L-functions have their zeros in the most natural place, the amount of mathematics unlocked is infinitely larger. So in a sense, mathematicians already know much of what proving Riemann right would unleash—it's already in the literature, awaiting this one big missing piece.

So where is that piece? "The Riemann hypothesis has had a few good ideas over the years, but none of them have really gotten to the nut of the matter," says Andrew Granville, a mathematician



The Riemann zeta function defines the sum of an infinite series involving a number with both a real and an imaginary part. It governs the locations of the prime numbers, the most fundamental objects in number theory.

at the University of Montreal. "They all ran out of steam early."

Two years ago two well-known mathematicians, Maynard of Oxford and M.I.T.'s Larry Guth, made the biggest breakthrough on the subject of the Riemann hypothesis in decades. All anyone had proved was that none of the zeros is too far from the critical line. But this boundary had been stuck for so long that people were starting to think it couldn't be pushed further. "I genuinely thought there must be some intrinsic reason that it was stuck," Granville says.

By developing entirely new techniques in number theory, Maynard and Guth managed to tighten the bound slightly—but only slightly. "These are two of the most brilliant people around, and even they got this marginal improvement," Granville says. And there is no clear way to proceed. "I don't really view our work as the right direction for solving the Riemann hypothesis," Maynard says. "I think of our work as more of a workaround for the fact that we don't know how to solve the Riemann hypothesis."

In a way, this difficulty makes it math's most and least popular conjecture. Mathematicians focus their efforts on problems within a sweet spot: hard enough (given current methods) that people care about solving them but easy enough that they might make some headway.

To Maynard, the lack of any clear route to solving the Riemann hypothesis is part of what makes the problem so important. It's a hint that whatever the route is, it will come only by way of lots of new mathematics. "I think the Riemann hypothesis is true for a really good reason. I just have no idea what that reason is," Maynard says. A proof that elucidates that reason, he says, would bring with it all kinds of far-reaching insights—a mastery of numbers that would open untold mathematical doors. It's the veiled contents of this mythical proof that so beguile mathematicians they would cede their autonomy to a large language model to see them.

"Provided I could understand the proof, be it from an alien or God or AI," Maynard says, "I would be superexcited." ●

FROM OUR ARCHIVES
The Biggest Problem in Mathematics Is Finally a Step Closer to Being Solved.
Manon Bischoff; ScientificAmerican.com, July 1, 2024.
ScientificAmerican.com/archive

The New Moon Race

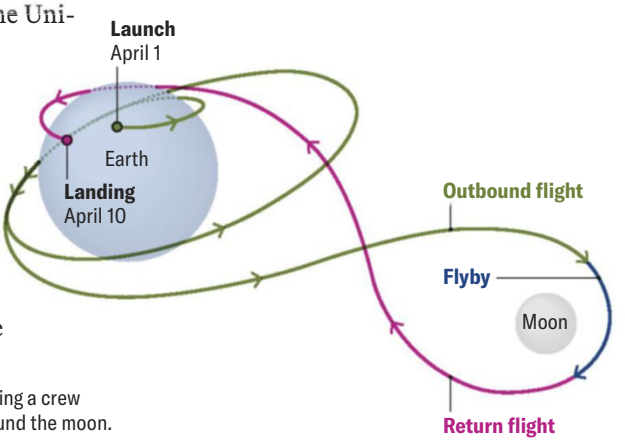
The triumphant Artemis II mission marks a new era of lunar exploration and science. Here's how it went down and what comes next

BY NADIA DRAKE

FOR SEVERAL DAYS IN APRIL, FOUR HUMANS LIVED CLOSER TO another world than to our own. By the time they splashed down in the Pacific Ocean, the crewmembers of NASA's Artemis II mission had flown farther from Earth than anyone else ever had. They became the first people to rendezvous with the moon in nearly 54 years. And for the first time, a woman's braids floated in deep space, an astronaut of color piloted a moon ship, and a Canadian radioed home from beyond the moon's cratered farside.

But these four astronauts—commander Reid Wiseman, pilot Victor Glover, mission specialist Christina Koch, and mission specialist (and rookie Canadian astronaut) Jeremy Hansen—represent more than a superlative series of firsts. Through their unwavering focus on joy and unity, the Artemis II astronauts forged a path forward not only in space but arguably on Earth as well. "This mission was about the way back to the moon, but I think it was also a way back to ourselves, to a more perfect union—or our better angels, whatever metaphor you want to use," says Jordan Bimm, a space historian at the University of Chicago.

AT 6:35 P.M. EDT ON APRIL 1, ARTEMIS II blasted off from NASA's Kennedy Space Center. As it leaped from the pad, the hulking Space Launch System (SLS)—a 322-foot-tall rocket flanked by boosters emblazoned with a patriotic logo celebrating the 250th birthday of the



The Artemis II mission launched on April 1, carrying a crew of four astronauts on a looping 10-day flight around the moon.

Nadia Drake is a freelance science journalist who specializes in covering space science and space exploration. Her work has appeared in the *New York Times* and the *Atlantic*, among other publications.

NASA/Bill Ingalls (*photograph*); Source: NASA (*graphic reference*)

Graphic by Amanda Montañez

The crew of Artemis II waves to family and friends shortly before boarding their Orion spacecraft atop the SLS rocket. From right to left, they are: NASA astronauts Reid Wiseman, commander; Christina Koch, mission specialist; Victor Glover, pilot; and CSA (Canadian Space Agency) astronaut Jeremy Hansen, mission specialist.

NASA/Aubrey Gemignani

U.S.—shook the ground for miles around. Some 400,000 spectators had flocked to Florida's Space Coast to witness the pyrotechnic performance in person. Millions more watched online as Artemis II soared into history.

Tucked into the Orion spacecraft atop the rocket, the mission's crewmembers had embarked on the first astronautical moon mission since 1972's Apollo 17. By design, Artemis II would not land on the lunar surface. Instead, somewhat like 1968's Apollo 8 mission, the crewmembers would follow a looping path that slung them around the moon before returning them to Earth.

Their flight path first traced two orbits around Earth, which the crew used to test the spacecraft's flight capabilities and onboard systems. Then the Orion capsule—which the astronauts named *Integrity*—fired its main engines in a "translunar injection burn" and set sail for the moon. It took about four days to reach the moon's sphere of influence. Once there, *Integrity* followed a trajectory that took it far beyond the lunar farside, ultimately flying 252,756 miles from home and making the Artemis II crew the farthest-flung humans in history. "As we surpass the furthest distance humans have ever traveled from planet Earth," Hansen said, "we do so in honoring the extraordinary efforts and feats of our predecessors in human space exploration."

Artemis II was the first in a planned yearslong series of crewed deep-space missions that, if successful, will culminate in the construction of a multibillion-dollar moon base at the lunar south pole sometime in the 2030s. "We have a lot of ambitions for the moon," says Lori Glaze, acting associate administrator of NASA's Exploration Systems Development Mission. "Our intent is to build that enduring presence on the moon and, in particular, at the south pole, where no one has ever been before. And the first step in making that happen is Artemis II."

The mission debuted more than three years after the uncrewed Artemis I flight, and it had a similarly rocky path to the pad. Propellant leaks and other issues with ground systems and the SLS rocket delayed Artemis II by months. Amid those delays, NASA leaders revamped much of the Artemis program's architecture, which now includes an additional crewed flight before the Artemis IV moon landing, an increased cadence of missions and, going forward, decreased reliance on the budget-busting and finicky SLS to get there.

These plans would have been tough to realize if Artemis II had not been successful. Now, though, we are once again a moon-faring species. "For the past 60 years, almost, more than a gen-

eration has not experienced people exploring beyond low-Earth orbit. That's a big deal," says Lori Garver, former deputy administrator at NASA. "To be getting back to that and to be doing it in a way that we hope leads to the kinds of discoveries you can get only when you're going beyond where we've been before—hopefully, most of us will agree that is important."

THE PARALLELS BETWEEN APOLLO 8 AND Artemis II go beyond their mission profiles; both also launched in eras of remarkable global turmoil.

In the late 1960s the U.S. was about as divided as it's ever been since the Civil War. Nearly six decades ago the nation was riven by protests over the Vietnam War, the impacts of the widespread Civil Rights Movement, and the assassinations of Martin Luther King, Jr., and Robert F. Kennedy. Amid that upheaval, Apollo 8 took flight. On Christmas Eve in 1968, the crew participated in a live television broadcast from lunar orbit. And by the time the spacecraft splashed down in the Pacific Ocean, its astronauts had snapped one of the space age's most epochal images: *Earthrise*, in which our lonely aquamarine marble gleams above a barren lunar landscape.

The crewmembers received millions of telegrams after their return, but one in particular stood out: it said, "You saved 1968." It seemed that—at least for some—the cold war–fueled space race with the Soviet Union had delivered a powerful moment of unity and inspiration in America, if not across the entire globe. "If there were a moment where spaceflight did have the power to mend societal factions, it would have been in 1968," Bimm says. "Space technology and exploration were this proxy for national prestige and national might during the cold war—it was this focus of urgency and geopolitical strategy. Today the technology that holds that place is artificial intelligence."

Both Apollo 8 and Artemis II were launched in eras of remarkable global turmoil.

Nearly 60 years later the U.S. is again at a crossroads, embroiled in an unpopular war and with a polarized populace facing a potential economic downturn at home. And a second space race is arguably unfolding, this time between the U.S. and China, which also harbors lofty lunar ambitions. As a nod to Apollo 8, the Artemis II crew chose a zero-*g* indicator inspired by the *Earthrise* image: Rise, a smiling plushie moon wearing an Earth-patterned baseball cap.

Even the calendar conspired to draw comparisons: it's not Christmas, but Artemis II's astronauts entered the moon's gravitational sphere of influence on Easter, another prominent day in

Spectators watch the launch of the Artemis II mission from the Banana Creek viewing site at Florida's Kennedy Space Center.

NASA/Keegan Barber

the Christian calendar. "Whether you celebrate [Easter] or not, whether you believe in God or not, this is an opportunity for us to remember where we are, who we are and that we are the same thing, and that we gotta get through this together," Glover said during an impromptu exchange about the holiday. "I think maybe the distance we are from you makes you think what we're doing is special, but we're the same distance from *you*. And I'm trying to tell you—just trust me—*you* are special."

Despite the parallels, spaceflight occupies a very different place in today's collective consciousness than it did during the Apollo era. "We are living in a booming space age that doesn't necessarily pierce the public consciousness each time some Starlink satellites go up," says Margaret Weitekamp, a historian and curator at the Smithsonian Institution's National Air and Space Museum. But human spaceflight is different—especially a test flight such as Artemis II. "It takes some courage and daring to do that—to be the test pilots on a system like this," says Clay Mowry, CEO of the American Institute of Aeronautics and Astronautics. "Every time we put humans into space, I get a knot in my stomach."

> "Every time we put humans into space, I get a knot in my stomach."
>
> —CLAY MOWRY *AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS*

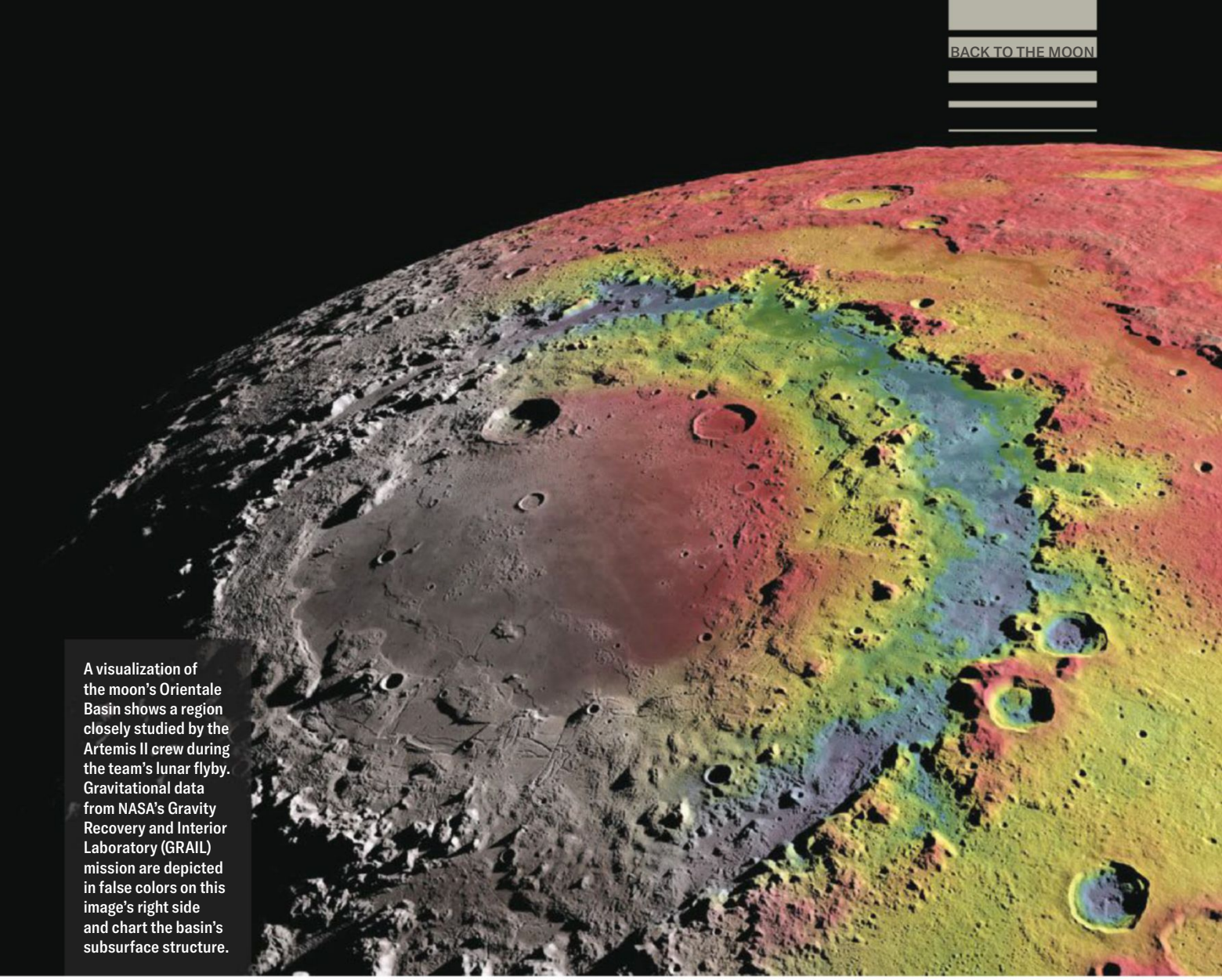
ALTHOUGH ARTEMIS II WAS THE RESOUNDing success that NASA needed, not everything worked perfectly. In particular, the mission's 3D-printed titanium toilet—the first ever to fly to the moon—malfunctioned. But the crewmembers handled the plumbing problem without losing sight of their priorities, which included studying the moon's cratered farside, which is hidden to human eyes here on Earth.

During Artemis II's seven-hour lunar flyby, the moon as seen through *Integrity*'s portholes was about the size of a basketball held at arm's length. The crew studied its surface, noting subtle greens and browns that had gone unnoticed in satellite imagery. The astronauts even saw flashes of light produced when micrometeorites smash into the moon's crust—an observation that prompted whoops and hollers from the science team in mission control. And as they swung around the moon, the crewmembers witnessed an otherworldly spectacle: a total solar eclipse in which the moon's silhouette loomed so large it obscured the sun for nearly an hour, revealing a handful of planets and a bottomless, star-stuffed cosmos. "It's indescribable. No matter how long we look at this, our brains are not processing this image in front of us," Wiseman said. "It is absolutely spectacular, surreal. There's no adjectives. I'm going to need to invent some new ones to describe what we are looking at."

Back home, the team in Houston had already coined a new term to capture the Artemis II crew's overwhelming happiness and excitement: moon joy. And for a few days, as people around the globe stayed glued to NASA's live stream of the mission, that joy spread from moon to Earth. "I don't think I've seen any time in the past when there's been this kind of collective swoon for the dynamic of a crew before," Bimm says. "A lot of people like what they saw from the crew and the virtues they were pretty consistent in extolling—teamwork, respect for others, love, stewardship of Earth."

The mission hit its most emotionally resonant note when the astronauts spoke to mission control shortly before their lunar flyby. Among the many landmarks they'd noted on the lunar surface were two small, unnamed craters. The crew wanted to name one Integrity, after their spaceship. And as for the other, a luminescent dot on the moon, "we would like to call it Carroll," Hansen told Houston, his voice breaking. "We lost a loved one. Her name was Carroll, the spouse of Reid, the mother of Katey and Ellie." Wiseman's wife had died from cancer in 2020.

Carroll Crater rests along the boundary between the moon's nearside and its enigmatic farside. And you can sometimes see it from Earth—a bright spot that will forever signify the humanity that Artemis II's crewmembers brought to their mission. Regardless of what NASA ultimately builds on the moon, Carroll Crater will always be there, reminding us of what it means to put the "human" in human space exploration and perhaps guiding us to venture ever farther from home with heart and humility. As Koch said after returning to our planet, we humans are the crew of spaceship Earth, an almost impossibly perfect oasis in the void of space. And we are in this together, just as surely as Earth and its moon are inextricably linked, locked in an endless celestial dance. ●



A visualization of the moon's Orientale Basin shows a region closely studied by the Artemis II crew during the team's lunar flyby. Gravitational data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission are depicted in false colors on this image's right side and chart the basin's subsurface structure.

NASA's Scientific Visualization Studio

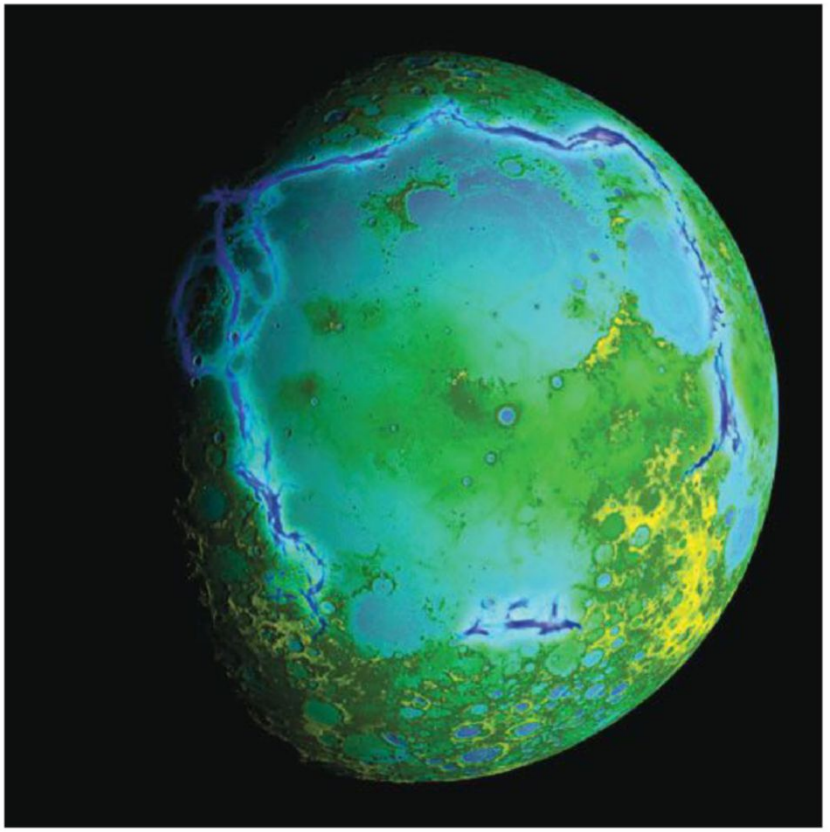
Lunar Geology

If NASA's ambitious lunar-exploration plans succeed, scientists will cover the moon with sensors—and find answers to several long-standing questions about the inner solar system BY ROBIN GEORGE ANDREWS

AT NASA'S "IGNITION" EVENT this March in Washington, D.C., the agency's administrator, Jared Isaacman, made it clear that Artemis II is only the beginning of a larger U.S. effort to populate the moon with astronauts and resource-prospecting robots. If this quest advances at the breakneck pace Isaacman desires, then Earth's celestial sidekick will also become a source of profound scientific revelations.

Despite the moon's proximity, we know surprisingly little about it with much certainty. The Apollo astronauts hauled back moon rocks and left behind a few short-lived geological experiments, but most of our lunar knowledge comes from moon-orbiting satellites, telescopic observations from Earth and the handful of sample-return missions undertaken recently by China.

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



A false-color topographic lunar view centers on Oceanus Procellarum, the largest expanse of frozen lava on the moon. Based on data from NASA's Lunar Reconnaissance Orbiter, as well as the space agency's GRAIL mission, the blue border structures are thought to be ancient, lava-flooded rift zones buried underneath Oceanus Procellarum's volcanic plains.

NASA/Colorado School of Mines/MIT/GSFC/Scientific Visualization Studio

Plenty of researchers are itching to use the moon as a Rosetta Stone for studying the origin and evolution of our world and the solar system at large. Earth's tectonics, volcanism, oceans, atmosphere and life have all erased the geological records of the planet's earliest eras. But the moon, lacking such tumult, has preserved its historical evidence. That makes the silvery orb "a perfect geological laboratory," says Sara Russell, a planetary scientist at London's Natural History Museum. With new lunar access, here are the biggest mysteries moon-focused scientists are hoping to solve.

How is the moon still geologically alive?

The churning heat deep within planets and moons is what gives them geological "life," from volcanic eruptions and earthquakes to the uplifting of mountains and the excavation of ocean basins. But when the heat wanes, a world dies, geologically speaking.

Scientists know of three main ways for those metaphorical fires to keep burning. Planets and moons possess a certain amount of primordial heat left over from the collisions of bodies that formed them. Decaying radioactive elements also emit heat. And the tidal forces that knead a world's innards like dough produce frictional heat.

The moon is much smaller than Earth, so its primordial heat should have leaked into space long ago. Lunar samples and theoretical models suggest it doesn't have a hidden abundance of radioactive elements. And careful calculations show that Earth's gravitational pull shouldn't be causing significant lunar tidal heating. Yet shallow quakes still shake the moon, and age estimates based on crater counts along its pockmarked surface suggest it was volcanically active as recently as 100 million years ago—which, on geological timescales, is yesterday.

Scientists, naturally, have questions. "Is the moon still volcanically active?" asks Thomas Watters, a senior scientist at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies in Washington, D.C. To find out just how much geological life still lingers there, and why, "we need to get a better look at the moon's internal structure," Watters says.

To delve to the (geological) heart of the matter, scientists want to know the moon's deepest secret: what's happening at its most abyssal depths. "Does the moon have a solid core or a liquid core?" asks Yuqi Qian, a lunar geologist at the University of Hong Kong. "We still don't know."

With seismometers, scientists can use moonquakes (caused by either internal rumblings or meteoroid strikes) to effectively perform a CT scan of the moon's deep subsurface. But the seismometers that the Apollo astronauts placed on the moon stopped working in 1977. Even if they were still operating, they're all located in just one patch of the moon's nearside. "We don't have any seismometers deployed on the farside," Qian says.

That's about to change. If current projections are to be believed, the Artemis IV mission will put astronauts on the moon in 2028. When those crewmembers reach their landing site near the moon's south pole, they'll tote along a cutting-edge seismometer package called the Lunar Environment Monitoring Station. Eventually, as part of a NASA initiative called Commercial Lunar Payload Services, robots will deploy a network of sensors on the moon's farside called the Farside Seismic Suite. "Artemis astronauts will be laying down some of the first nodes of a global seismic network," says Nicholas Schmerr, a seismologist and planetary scientist at the University of Maryland, College Park. (China may make its first crewed landing somewhere on the moon's nearside, and those astronauts will probably bring seismometers as well.)

Seismometers aren't only great at interrogating the mysteries of the lunar interior; they can also be used to work out just how seismically active the moon is today. Moonquakes, which at their strongest can persist for hours, could

imperil a future moon base. "You don't want to think of the moon as this benign place," Watters says. "You really need to understand whether you have threats to long-term infrastructure from seismic activity."

To understand the moon's geological heartbeat, samples, too, will be vital. Rocks carried home by China's robotic lunar-sample-return missions, Chang'e 5 and Chang'e 6, indicate that the moon hosted active volcanism until at least two billion years ago. Widening our view to the moon's more recent history requires nabbing more youthful material from its surface. For now, Qian says, "we don't have samples younger than that."

Scientists also hope future landings will locate and sample expunged sections of the moon's mantle, the primeval underbelly of the lunar crust. If mantle rocks proved to be riddled with by-products of radioactive decay, it would probably mean the moon's interior is richer in heat-generating radioisotopes than scientists had thought—thus explaining why it's still convulsing long past its geological expiration date.

How did the moon form?

The moon's most popular origin story involves Theia—a Mars-size protoplanet—smashing into the primordial proto-Earth, with the debris from both bodies quickly coalescing into the moon. This account isn't just a fable: it's backed up by robust computer simulations grounded in plenty of geochemical evidence. Samples of the moon's mantle, though, could further test this theory—and geophysical observations could address the moon's weirdest feature.

The nearside is covered in vast, dark splotches of cooled volcanic rock called mare (Latin for "sea"). The farside looks more like Mercury: a crater-filled land of jagged mountain ridges. Why is the moon so two-faced?

One possible explanation comes from an idea called Earthshine. Eons ago, when the moon formed, its orbit was 15 times closer to Earth than it is now. At some point the moon became tidally locked, meaning one hemisphere (the nearside) always faced Earth. And because back then our planet was a seething ball of magma, the lunar nearside should have gotten baked like crème brûlée, turning molten and bubbly. Streams of vaporized rock whooshed around the moon, cooling and raining down on the farside to create its thick, lumpy crust. A network of seismometers, especially on the farside, could reveal hidden clues to the lunar past. "What is the structure of the moon?" Russell asks. "This is important to find out because it will help us understand how the moon first formed from the debris of a giant impact and then evolved."

Where did the moon's water come from?

NASA wants to set its astronauts down near the lunar south pole because that's where permanently shadowed craters hold some amount of water ice—a potential resource for hydrating humans, growing crops and making rocket fuel at a permanent moon base. It's no coincidence, then, that lunar prospecting was a hot topic at NASA's Ignition event. Astronauts could, in principle, descend into the treacherously dark and cold craters themselves to take a look, but most of this water divining will be conducted by robots.

NASA's Volatiles Investigating Polar Exploration Rover will use its instruments to sniff out subsurface water, then drill to confirm its suspicions. And NASA's next-generation moon buggy—or Lunar Terrain Vehicle—will do something similar while either being piloted by astronauts or autonomously navigating the surface. And on an upcoming crewed mission, astronauts are set to bring along the Lunar Dielectric Analyzer, an instrument that can detect electrical currents in the ground below, which can reveal the presence of ice. "This will really help us understand where water is on the moon and in what form," Russell says.

The search for water isn't just pragmatic. Scientists still don't really know where Earth's water came from. Ice-rich comets and drier asteroids are the two prime suspects. Geochemical studies of meteorites and Earth's oceans suggest that asteroids were the more likely vector, but the case is far from closed. Consulting the moon's relatively pristine terrain—much of which has been frozen in time for billions of years—could help solve this mystery. "If there's any water ice on the moon, its signal might be more primitive," Qian says. And because Earth and the moon have a very similar ancient history, "the origin of water on the moon is likely to be the same as the origin of water on Earth," Russell says. All scientists need to do now is find it. ●

Moonquakes, which at their strongest can persist for hours, could imperil a future moon base.

Eyes in the Sky

The Artemis moon missions are a game changer for astronomy

BY JOSEPH HOWLETT

As the U.S. government slashes its spending on basic science, one thing seems certain: there's still plenty of money for going back to the moon.

NASA's Artemis II mission is only the tip of the space agency's lunar-exploration spear; planning for crewed and robotic follow-ups is well underway. And all of these other trips could involve equipment for groundbreaking research, too.

There's a lot to learn on the moon. Most of it is about the moon itself—its murky origins, its expansive history and even the vital resources it might hold. But some astronomers, faced with increasingly austere government funding for their ground- and space-based projects, are beginning to see the moon as a more stable stage for some of their most ambitious cosmic studies.

Anže Slosar, a physicist at Brookhaven National Laboratory in New York State, had once hoped to put a radio telescope on the farside of the moon but abandoned his dream years ago. The mission just seemed too expensive, and there wasn't enough interest in it. "After the Apollo landings, the thinking was, 'We've done it,' and that was that," he recalls. Sentiments changed during the first Trump administration. One day Slosar got an e-mail from a Department of Energy program director asking him whether he still thought building a farside radio telescope was possible and whether he was interested in leading the DOE's involvement with such a project. It was the easiest choice of his professional career. "I said, 'Of course!'" he recalls. "It changed my life forever."

The reason for Slosar's enthusiasm is that a radio telescope on the moon could do things none on Earth can. Radio telescopes on the ground can collect signals from only a limited range of wavelengths. That's because as air molecules in the upper atmosphere soak up the sun's ultraviolet rays, they get so excited that they shed their electrons, becoming ionized. For most radio waves, the resulting ion-filled layer—the ionosphere—is like a giant mirror, blocking many inbound cosmic messengers.

The solution isn't as simple as launching a radio telescope into space. To be of much use to radio astronomers, any spaceborne observatory would need to be exquisitely sensitive—so sensitive that its observations would be swamped by telecommunications emanating from Earth. To tune in to distant galaxies and other faraway objects, astronomers would need an antenna in a place with no atmosphere that also would be somehow protected from all our terrestrial chatter.

Such a place exists, of course, and it's only a proverbial stone's throw from the third rock from the sun. Earth is locked in a synchronous dance with the moon, so the same lunar hemisphere always faces away from us. On that farside surface, the moon itself acts as a shield from Earth's cacophony of radio signals. This obstruction is exactly why Houston Ground Control lost contact with the Artemis II crew for about 40 minutes during the April 6 lunar flyby, when the mission's Orion spacecraft was masked by the moon. "Behind the moon, at the right time, you can avoid interference from both the sun and Earth," Slosar says. "It becomes one of the quietest places in our solar system for observing these radio frequencies."

That span of wavelengths happens to be a window into the most mysterious epoch of the universe's history.

Our oldest snapshot of the universe comes from some 380,000 years after the big bang. It is known as the cosmic microwave background, or CMB, and is made up of the light that was released when the hot, dense plasma that suffused the early universe cooled enough to form hydrogen atoms. Much like the radio-blocking swarms of electrons in Earth's ionosphere, unbonded electrons in that ancient, ionized plasma blocked light, too—so when they all settled down into

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NASA

The farside of the moon as viewed by the crew of the Artemis II mission. The moon blocks all radio waves from Earth, so it's an ideal place to gather them from the cosmos.

atomic hydrogen, light that had spent millennia hidden by the primordial fog was liberated to stream freely across the universe. Today we see this "last scattering surface" as a diffuse all-sky radio glow.

But we have essentially no data at all about the cosmos for hundreds of millions of years after that singular moment in time. That's because the universe was full of relatively cool, light-smothering hydrogen, which emitted scarcely any light of its own. Only when stars and galaxies started forming from all that hydrogen was there enough light and heat to reionize some of the hydrogen atoms, making those growing cosmic structures visible to our telescopes.

There was a bit of light in the so-called cosmic dark ages, though: a faint trickle of 21-centimeter-wavelength radio emissions emanating from the hydrogen atoms. Astronomers have managed to detect some 21-centimeter cosmic signals through heroic efforts using ground-based instruments, but the noisy, patchy view painted by these detections is woefully incomplete. To map the dark ages in all their hidden majesty—to discover how, exactly, cool matter coalesced into luminous cosmic structures—the best option, by far, is to search from the farside of the moon.

That is where Slosar comes in. He now directs the DOE's contributions to its partnership with NASA on a project called the Lunar Surface Electromagnetics Experiment–Night (LuSEE-Night), which aims to launch to the lunar farside in December 2026. It will fly onboard a Blue Ghost lander from Firefly Aerospace as part of NASA's Commercial Lunar Payload Services (CLPS) initiative, which relies on landers built and operated by private industry to deliver spacecraft, experiments, and other payloads to the moon's surface.

Once LuSEE-Night reaches its destination, its greatest challenge will be getting through the cryogenically cold lunar night, which lasts for the equivalent of about 14 Earth days. Pink Floyd might have misled you: the moon's farside isn't always dark. When it is, though, it's an inhospitable place—few experiments have survived the night. Ultimately the mission is meant to be a pathfinder, proof that even larger and grander radio telescopes can be built and operated on the moon's farside.

A FREE TRIP TO THE MOON would be a dream for the newest additions to the ranks of astronomers: those who study the universe by investigating gravitational waves.

The moon may be a more stable stage for astronomers' most ambitious cosmic studies.

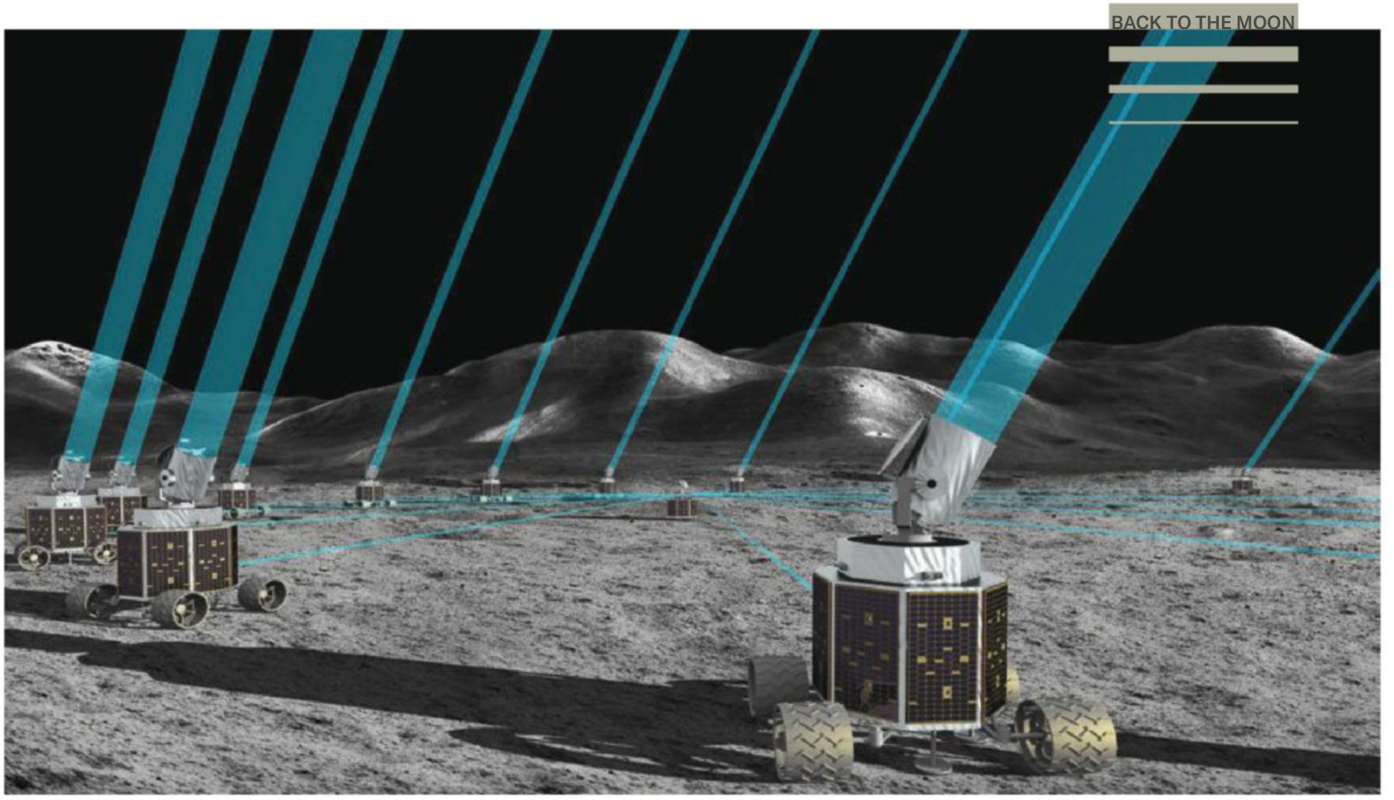
It was just 11 years ago that humans gained the ability to scan the skies for these elusive waves, using the Laser Interferometer Gravitational-Wave Observatory. Better known as LIGO, this project uses lasers to sense the subtle stretching of space and time caused by the cataclysmic merging of two gigantic black holes.

The European Space Agency's upcoming Laser Interferometer Space Antenna (LISA) mission—essentially LIGO in space—will expand on the revolution LIGO started. Launching as soon as 2035, LISA could sense waves from mergers of black holes that are far more massive than those within LIGO's purview. It will also spot the slower ripples of calmly orbiting binaries, emitted long before their death spiral begins. Both of these sources make waves with millions of kilometers between peaks, too long for any Earth-based instrument to register.

To complete their coverage of the gravitational-wave spectrum, astronomers have their eyes on the moon. The Laser Interferometer Lunar Antenna (LILA) would close the gap between LIGO and LISA by tuning in to waves with intermediate wavelengths. These signals would include those from the mergers of white dwarfs, the astronomical objects that produce many of the supernovae we observe through their electromagnetic emissions. LILA would also capture the gravitational waves from neutron star and black hole binaries just as they began their final descent toward coalescence, providing an early-warning system that could alert LIGO to collisions two weeks before they happened. "There is no other place in the solar system where you can detect gravitational views in this mid-band," says Karan Jani, an astrophysicist at Vanderbilt University who is a principal investigator of the LILA project. "There is only the moon."

That's because the moon is much more geologically inert than our rowdy planet. "It doesn't have as active a core," Jani says, meaning the lunar surface can be a quiescent platform for gravitational-wave-spotting laser systems custom-made for the mid-band.

LILA will essentially be built of mirrors mounted on rovers. The project team hopes to hitch a ride on an upcoming CLPS mission. When the lander opens onto the lunar surface, two rovers with mirrors will head in different directions, forming a triangle with five-kilometer-long sides, with the lander as the triangle's third point. Then an instrument on the lander will beam lasers out-



Britt Griswold/GSFC

The Artemis-enabled Stellar Imager (AeSI) will use an array of mirrors mounted on rovers to take high-resolution photographs of faraway stars at every stage of their life cycle.

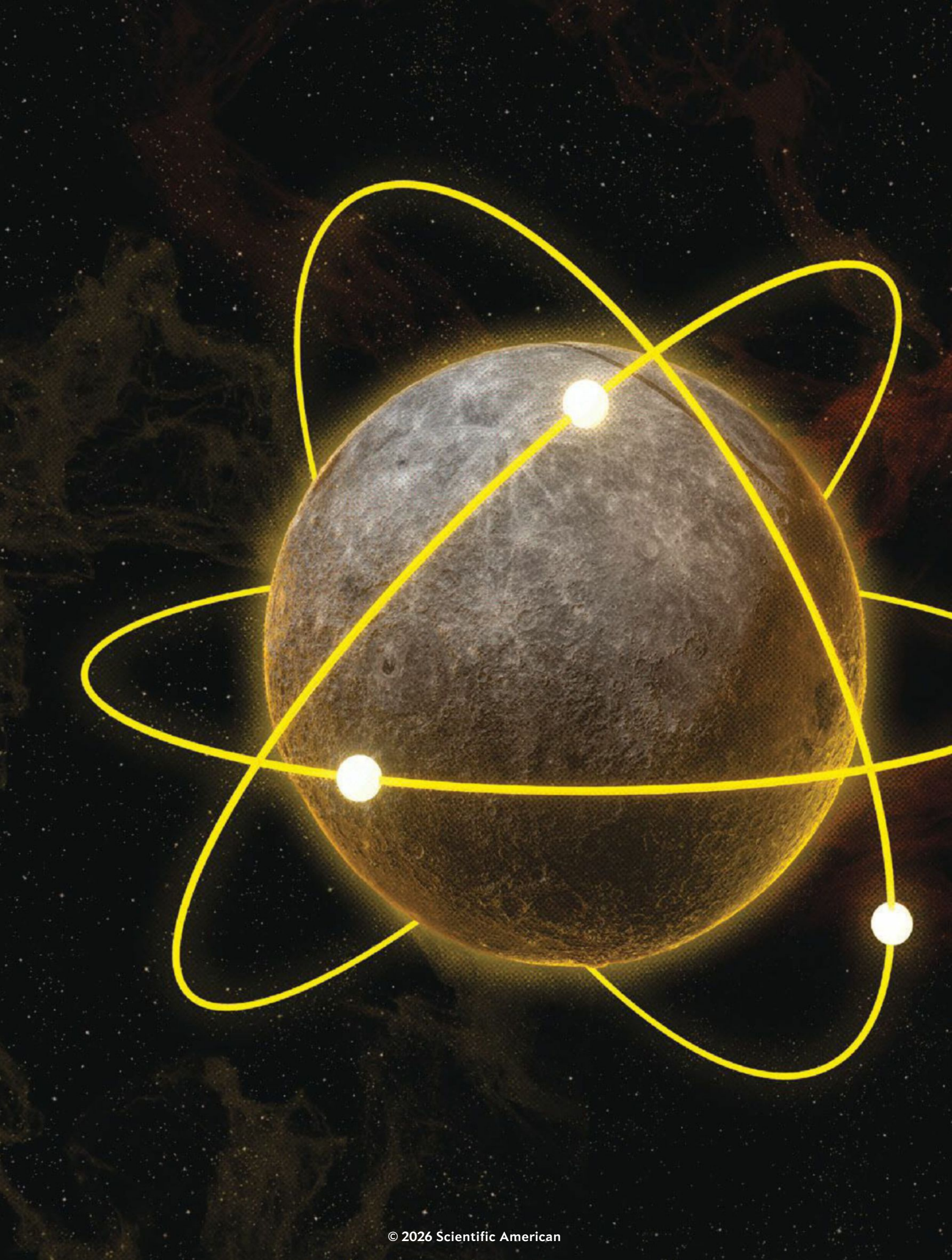
ward to the rovers to compare their distances with subatomic precision. "To be honest, we wouldn't be thinking about LILA if the United States were not going to the moon," Jani says. The LILA team is hoping to reach a later phase of the project that would be carried out in collaboration with NASA's Artemis program and rely on astronauts for operation and maintenance.

OBSERVATORIES such as the James Webb Space Telescope (JWST) and the Hubble Space Telescope—and, for that matter, your typical consumer-grade reflector telescope—are all based on the same design: a mirror curved just so to channel incoming light from many directions onto a single focal plane. Large telescopes use segmented mirrors to collect more light from faraway objects and produce a crisper image; JWST's primary mirror is composed of 18 sections.

Optical interferometry is a way to make a telescope's light-gathering surface far bigger by spreading out such segments over an even larger area. In this approach, individual mirrors are interlinked in an array, with each node channeling its light to a central facility that carefully corrects and combines these inputs, effectively forming a much more powerful telescope.

By piggybacking on the Artemis program, NASA scientist Kenneth Carpenter aims to build an optical-interferometry facility on the moon. This proposed Artemis-enabled Stellar Imager (AeSI) would consist of 15 to 30 rover-mounted mirrors, allowing for reconfiguration and other fine-tuning on the fly so the imager could fix on any target in the lunar sky. Besides being a potent technological pathfinder, AeSI could monitor many stars throughout a sizable swath of the Milky Way. By studying them in ultraviolet light that terrestrial observatories can't access because of Earth's UV-blocking ozone layer, the project could literally shed more light on the still-mysterious details of stellar activity across the galaxy. "We have wonderfully high-resolution data on the sun," Carpenter says. "But we still haven't come up with a good predictive model of future activity." Scientists' best solar models struggle to precisely predict flare-ups on our own, most familiar star. But the hoped-for expansive stellar datasets that AeSI could provide may help change that.

The project could also benefit from astronautical interventions, Carpenter says, meaning AeSI maintenance would be another possible task for the Artemis crews that NASA plans to land on the moon by 2028 and throughout the 2030s. If Carpenter's decades of experience working on the Hubble Space Telescope taught him one thing, it's that troubleshooting an experiment is infinitely more effective with a human on-site. "The space shuttle and Hubble were kind of designed with each other in mind," he says, pointing to the STS-61 mission in 1993, which included a spacewalk to fix a critical problem with Hubble's mirror. That historic telescope, Carpenter says, "probably would have been a failure without the collaboration of the human spaceflight program." ●



A Nuclear Moon

NASA wants a nuclear reactor to power a lunar base. It's not as crazy as it sounds

BY ROBIN GEORGE ANDREWS
ILLUSTRATION BY TAVIS COBURN

LAST YEAR, LESS THAN A MONTH AFTER BEING NAMED acting administrator of NASA, U.S. Secretary of Transportation Sean Duffy made an eyebrow-raising announcement to the world: NASA was going to put a nuclear reactor on the moon. As part of strengthening U.S. national security in space, he said, this reactor would be designed, built, flown and delivered to the lunar surface by 2030. To many observers, this declaration sounded wild. Why would you want to put a nuclear reactor on the moon?

The thing is, if America (or any spacefaring nation) wants to establish a permanent presence on the moon—an inhabited station that can operate during the frigid and lengthy lunar night—solar power won't cut it. Through its Artemis program, which just sent four astronauts on a trip around the moon, NASA wants to transform our planet's argent companion into a scientific outpost, a mining site and a rocket launchpad pointed at Mars. To do that, nuclear power is the sole option. "It's the only way we can sustain a lunar base properly long-term," says Simon Middleburgh, co-director of the Nuclear Futures Institute at Bangor University in Wales. It's no wonder, then, that China and Russia are teaming up to put

their own nuclear reactor on the moon by 2035 to electrify what they call the International Lunar Research Station—their planned base on the lunar south pole. Sooner or later, from one nation or another, "nuclear power on the moon will happen," Middleburgh says. "It's inevitable."

Nuclear power plants are safer than many suspect. But putting reactors in space is a concept with a checkered history. One notorious reactor caused an international incident in 1978 after it came apart in Earth's atmosphere. And nobody has ever designed a reactor for the moon, a hostile volcanic desert subject to extreme temperature swings, frequent asteroid strikes and protracted quakes.

Experts questioned both the timing and the scale of the nuclear power plant Duffy is proposing. Placing a reactor capable of powering 80 American households on the lunar south pole—an environment no human has yet set foot in—by 2030 sounds rushed, if not impossible. And the last thing anyone wants is for the U.S. to barrel through the conception, construction, launch and landing of a lunar nuclear reactor. "I think the worst-case scenario might be [that] in the quest to be first we skip important design and safety steps," says Bhavya Lal, a professor of space policy at the RAND School of Public Policy and former acting chief technologist and associate administrator for technology, policy and strategy at NASA. "It's good to be first—competition is good—but we need to do it right."

If the U.S. does succeed, its nuclear-powered moon base could become a solar system–exploring foothold among the stars. But mistakes can happen. And whether you've accidentally spray-painted an ancient reserve of water ice with radioactive waste or fatally stranded your astronauts in the lunar darkness without any power, a nuclear disaster on the moon would be, in Middleburgh's words, "a humanity-defining shit show."

KATY HUFF WANTS TO CLEAR something up: uranium, the infamous radioactive element used to power nuclear plants and, with some tweaking, give most nukes their annihilative terror, is dull—at least in a manner of speaking.

Huff, a nuclear engineer at the University of Illinois at Urbana-Champaign, was the assistant secretary for nuclear energy in the Biden administration. Nuclear power is her jam. But it's important to know that unused nuclear fuel is "radiologically very boring," she said during a recent video call. "It's not particularly radioactive." She gestured to an object on her desk. "I have some uranium in that cardboard box right there." The fact that you can hold uranium in your hand without consequence may come as a surprise to many. "You can pick it up. It's toxic more than anything else; it's like lead," Middleburgh says. "So don't eat it."

Uranium becomes dangerous—and helpful—when you chuck it into a nuclear reactor and fire neutrons at it. The impact causes the uranium's unstable atomic nuclei to snap apart and emit more neutrons, which cause more nuclei to rupture—and voilà, you have a heat-emitting nuclear fission reaction. As long as the reaction doesn't spiral out of control, you can use the heat to turn a fluid (often water) into steam. That steam rotates a turbine, which makes electricity.

You don't want to hold the uranium fuel after it's been blasted with neutrons. "Then it breaks apart and becomes fission products that are highly radioactive, which is why nuclear waste is dangerous," Huff says. But because that nuclear cascade can continue for a very long time, it's a fabulous power source—particularly in space, where it won't need refueling for years, maybe decades.

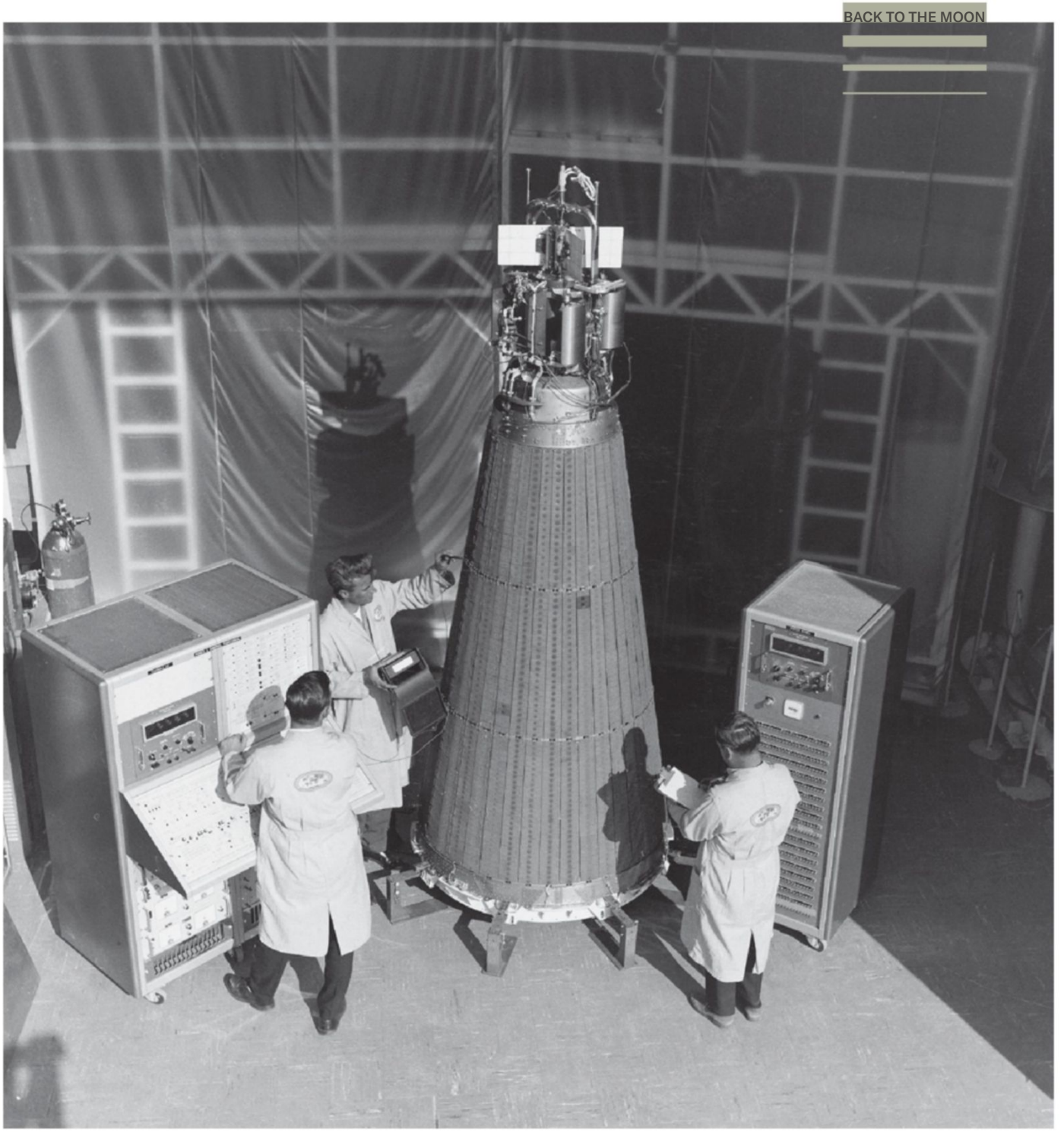
The concept of nuclear power in space isn't new. Starting in the 1960s, both the U.S. and the Soviet Union sent plenty of radioisotope thermoelectric generators, or RTGs, into space to power all kinds of things, from Earth-orbiting satellites and the Apollo-era scientific experiments on the moon to Mars rovers and deep-space probes. Plutonium, uranium's ferocious chemical cousin, was often used in these devices. RTGs, though, are not nuclear reactors. They are more like nuclear batteries: screaming-hot radioactive caches providing a small but lasting source of heat that can produce electricity.

But an RTG would be insufficient to power a moon base. Astronauts need more than just energy to keep the lights on. They need a constant source of heat in the night and a way to vent that heat when the mercury soars during lunar daytime. If they want machines that can extract precious water from the lunar soil—water for hydrating both astronauts and crops and, crucially, to be electrically split into hydrogen and oxygen gas to make rocket fuel—then they'll need oodles of electricity to power them.

It makes sense, then, that for the past several years, across both the first Trump administration and the Biden administration, NASA and its industry partners had been working on designs for a 40-kilowatt lunar reactor. This size would be enough to power an office building, which is about right for a prototypical moon base, experts say.

Under Duffy's brief tenure as NASA's leader, that number jumped to 100 kilowatts. Why? "I have no idea," Huff says. "I found no evidence that they thought about that number beyond it

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



George Rinhart/Corbis Historical/Getty Images

The System for Nuclear Auxiliary Power (SNAP) 10A, which launched in 1965, was the first nuclear reactor sent to space. Heat from the reactor (*top*) was converted to electricity by the cone structure.

being bigger." Compared with a standard U.S. nuclear reactor on terra firma, 100 kilowatts is tiny—it's about 10,000 times less powerful, and it would be only the size of a large car. But this capacity is "huge for space," Huff says, noting that 100 kilowatts is a full order of magnitude greater than the output of any other nuclear reactor launched off-world.

Technically, putting a bespoke 100-kilowatt reactor on the moon in just four years is possible. "It is an aggressive but achievable goal," says Sebastian Corbisiero, national technical director for the U.S. Department of Energy's space reactor program.

In January, NASA's current administrator, Jared Isaacman, reaffirmed the plan to put nuclear fission power on the moon. And in March he announced that NASA would launch the first interplanetary spacecraft powered by nuclear electric propulsion—the Space Reactor-1 Freedom—to Mars by the end of 2028. This mission will help test out nuclear fission technology in deep space

before the U.S. establishes a nuclear power plant on the lunar surface.

"I am quite confident that no reactor the U.S. launches will have safety concerns," Lal says. Yet "obviously things can always go wrong, and there's no such thing as 100 percent safe anywhere in the world—and anybody who says [they've achieved] that is lying."

TO PUT A NUCLEAR REACTOR on the moon, you must first put it on a rocket. "Keeping it safe for launch is one of the biggest factors," says Lindsey Holmes, an expert in space nuclear technology and vice president of advanced projects at Analytical Mechanics Associates, an aerospace company based in Virginia.

The U.S. launched the first nuclear reactor to space, the experimental Systems for Nuclear Auxiliary Power 10A reactor, back in 1965. This waste-

Technically, putting a bespoke 100-kilowatt reactor on the moon in four years is possible.

basket-size 600-watt box generated power for just 43 days before a voltage regulator broke. It's still orbiting the planet today and remains America's sole attempt at operating a nuclear reactor off-planet.

The Soviet Union, in contrast, propelled more than two dozen nuclear reactors beyond Earth's atmosphere. Most of these reactors, which were often used to power radar spy satellites, went up without incident. One, however, "spewed radioactive stuff all over Canada," Holmes says, providing a brutally instructive master class in what not to do.

The spacecraft carrying that reactor, the Kosmos 954, started moving off target about three months after its September 1977 launch. Both the Soviet Union's operators and the U.S. officials noticed it wobbling around, but the Soviets initially kept quiet. Their engineers tried to eject the satellite's active nuclear reactor into space before the vehicle crashed back to Earth, but to no avail. Eventually the Soviets fessed up to their American counterparts—but they claimed Kosmos 954 would incinerate without consequence during its by then unstoppable atmospheric reentry.

U.S. authorities openly wondered what to do about a hot nuclear reactor plunging back to Earth. Gus Weiss, then a special assistant to the secretary of defense, said at the time that "a quick scan of literature showed no textbook answer, nor even a textbook question." Ultimately, in January 1978, Kosmos 954 showered its deadly detritus over a 15,000-square-mile patch of Canada's relatively sparsely inhabited Northern Territories. During a joint Canadian-American operation called Morning Light, hazmat-suited agents scoured the frozen realm for the shattered corpse of Kosmos 954. Some parts of the satellite weren't highly radioactive, but other fragments made the agents' personal radiation dosimeters sound off like "a field of crickets," according to a member of the team. Miraculously this trial by radioactive fire didn't kill a single soul—and the Soviet Union paid Canada $3 million CAD in apology. One clear lesson emerged from the Kosmos 954 kerfuffle: don't start a lunar nuclear reactor until it lands on the moon. "Until you turn it on, there's no nuclear waste inside," Huff says.

Ideally a lunar reactor should launch over the ocean because a splashdown would be a far better outcome than splattering a populous area with a smashed-apart nuclear reactor. The episode also revealed that the choice of reactor fuel is important, and you would want a fuel type that isn't prone to dispersing over a wide area. Tristructural isotropic particle fuel, better known as TRISO fuel, could work wonders here. It consists of pellets that are "basically gobstoppers of fuel," Middleburgh says. Each pellet is essentially a uranium, carbon and oxygen blob imprisoned within an ultraresilient carbon and ceramic shell. Not only can they survive high-velocity impacts fully intact, but you could pour lava over them to no effect. "If your launch were to fail, it'd be a big economic mess," Middleburgh says, but "you'd be able to sweep it all up."

MIDDLEBURGH, LIKE MANY of his colleagues, is enchanted by nuclear power. Unprompted, he waxes lyrical about the first time he saw Cherenkov radiation—an eerie blue glow—in a reactor pool: "TVs and pictures on the Internet don't do it justice. It's opalescent, magical; it's like the northern lights." But he's under no illusion that trying to put a working nuclear reactor on the moon, though entirely plausible, will be simple.

Let's start with the bad news: it's a lot easier to operate a nuclear power plant on Earth. The moon, quite frankly, is an awful place. It's a low-gravity world with essentially no atmosphere, which means its surface temperatures regularly swing from 250 degrees Fahrenheit during the day to –208 degrees F at night. It also has moonquakes, which resemble Earth's tectonic tremors but

are weirder, and frequent small asteroid impacts create hefty craters on the surface at random times and locations.

The good news is that nuclear reactors aren't as prone to cataclysmic explosions as you might think. If the machine gets too hot and can't cool down, it will melt. But meltdowns are not explosions. Modern reactors are designed so that if nuclear fuel liquefies, they contain it within the plant.

Nuclear power plants are not particularly fragile, either. "When we think of nuclear, we think of Fukushima, we think of Chernobyl," Middleburgh says. But along with the virtually countless nuclear power plants around the world that have been operating normally for decades, "we don't think of the ones that have been floating in our oceans." Nuclear submarines are also plentiful; they exist in a fairly extreme environment, get knocked around all the time and are designed to withstand combat scenarios. "These things can be seriously robust," he says. There's no reason they can't withstand the moon, too.

A nuclear disaster on the moon is possible, though. Let's say a nuclear reactor does overheat and creates the first-ever nuclear meltdown on the moon. That would be a truly ignoble achievement, but at least most of the melted fuel would be contained at the site. It would, however, mean that "there would be a large, radioactive hunk of metal sitting there on the lunar surface," Huff says. Nobody could approach it, perhaps for generations. And if it oozed into a precious reserve of water ice nearby, that game-changing resource—the entire reason astronauts would be based there—would be permanently contaminated. "Yikes," Huff says. "It would be terrible. It would be very hard to forgive a nation willing to do that to the moon." But at least the astronauts would be fine, right?

Well, not really. Radiation from the reactor—even what might be unleashed during a meltdown—wouldn't be a huge worry (in fact, the solar and cosmic radiation on the moon is much more of a concern for astronaut health). The failure of the plant would be the bigger problem. Say the lunar base relying on it loses electricity during the two weeks when any given spot on the moon is cloaked in darkness. In such cold conditions, battery systems may hold only a modicum of juice before they run dry. Then the astronauts are in deep trouble "because their entire life-support system goes down," says Nicholas Schmerr, a planetary seismologist and geophysicist at the University of Maryland, College Park. "They're not going to be able to survive."

But experts don't anticipate that we'll see a lunar Chernobyl in our lifetime. And a spokesperson at NASA says "the fission surface power system will be designed with safety in mind." That's a relief. A more realistic worst-case scenario for a 100-kilowatt nuclear reactor is that the moon simply breaks it, and it stops working when the astronauts need it most. So the real question is, "How long can we design all the sensors and electronics and all those components to last in a fairly hostile environment?" Corbisiero asks.

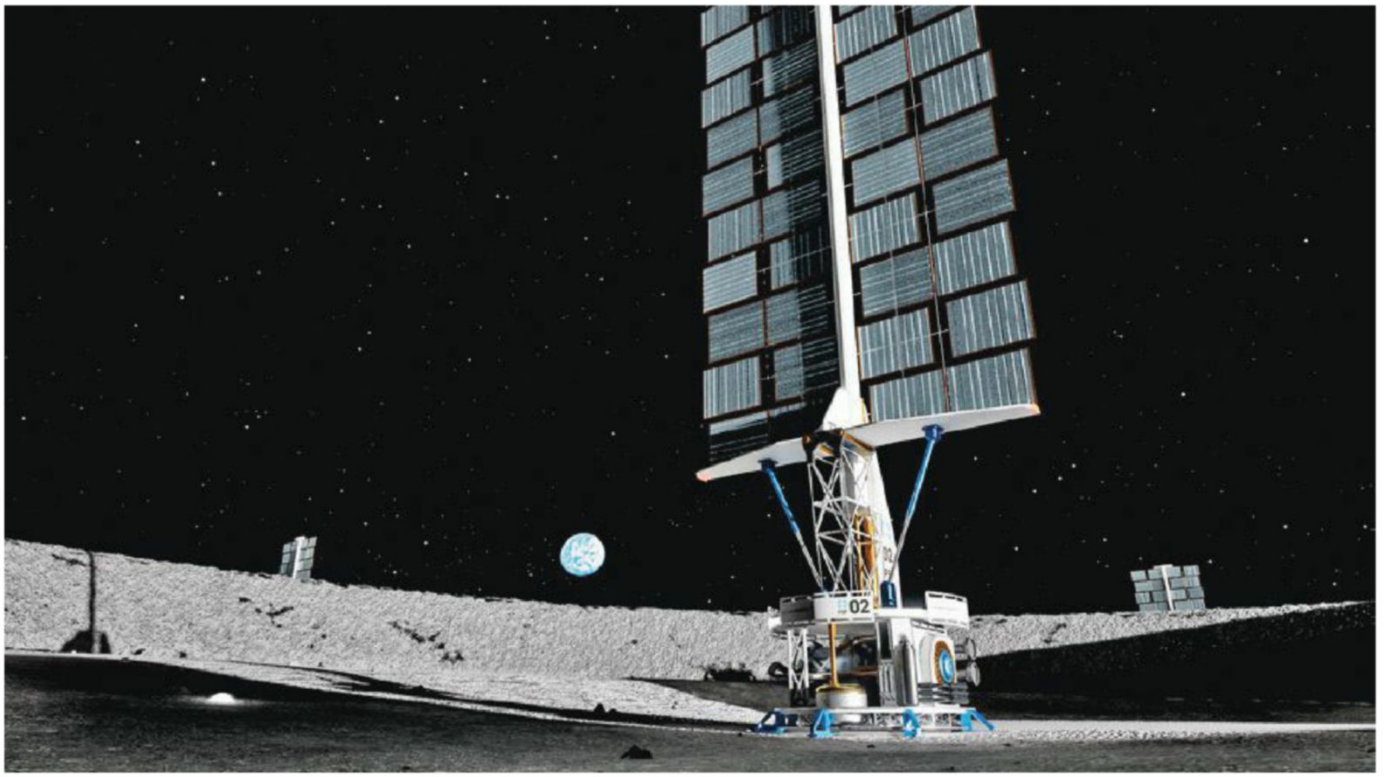
A LUNAR REACTOR WILL HAVE to function differently than those on Earth. It probably won't be able to use water either as a coolant or as the heat-absorbing, steam-making substance that turns a turbine to make electricity. "Water has a lot of problems in space," Huff says. It doesn't flow properly under low gravity, and the maddening temperature swings on the moon could cause the steam to violently expand or the water to freeze, breaking pipes in the process. Instead the reactor would probably use air brought from Earth to take on the heat and move it to the turbine. That's more difficult to design for, but it's possible.

Replacing water as the nuclear reactor's coolant is much more problematic. Most of the heat produced by the fissioning uranium would be used to make electricity, but some of it would be excess. This "waste heat" will need to escape into the environment, but without any atmosphere there won't be any airlike sink to easily soak it up. Stopping the nuclear reactor from overheating is "going to be hard in a vacuum," Huff says. She and Middleburgh suggest the same solution: sails—giant finlike adornments that can use their large surface area to eject heat into space.

Sounds good. But don't forget about those pesky micrometeorites—pebble-size rocks that move like hypersonic bullets. "The moon is constantly being bombarded by extraterrestrial material," Schmerr says, and there's no atmospheric shield to stop them. If several of these meteorites puncture the radiator fins, the plant will be unable to cool down properly.

You also could get supremely unlucky, and an asteroid a dozen or so feet across could smash into the ground nearby. "We saw new craters that formed during Apollo that were 70, 80 meters [230 to 260 feet] wide," Schmerr says. "If you happen to be at ground zero for one of those impacts, you're having a really bad day."

Astronauts cannot defend their base against any of these rarer, larger asteroid strikes. But they can mitigate the threat of the more frequent but



diminutive space bullets by burying their power plant underground. They wouldn't even need to dig—they could simply use one of the moon's multitude of hollowed-out lava tubes.

Moonquakes are another challenge. They are nowhere near as powerful as Earth's tectonic convulsions: the largest spotted by seismometers placed during the Apollo era were between magnitudes 3 and 4. Still, a nuclear power plant shouldn't go right next to a potentially active fault, because even a modest tremor could knock over taller structures and break things.

> "We don't want to *not* be the first to have a nuclear reactor on the moon."
> —BHAVYA LAL *RAND SCHOOL OF PUBLIC POLICY*

But the moon's geological makeup gives moonquakes a surprising persistence compared with earthquakes; the tremors can last for several hours. "Not only is your system shaking, it's shaking a lot for a long time," Schmerr says. "This is not something we normally think about with structural construction here on Earth."

If the reactor isn't properly fortified against the moon's seismic dangers, three things could happen: the reactor could break and stop working; the fuel might be jiggled around and put into a weird arrangement that slows down the fission reaction; or the fuel could shift in a way that speeds up the reaction—and makes the power plant overheat until it requires a shutdown before it turns into a lethal, incandescent soup.

NASA's experienced industry partners, its own deep expertise and its cutting-edge testing facilities will certainly help to make any reactor disaster-resistant. But it's impossible to perfectly recreate the lunar environment on Earth. Reproducing lunar gravity in a laboratory would require an act of witchcraft, and although vacuum chambers can simulate the moon's extreme temperatures and lack of atmosphere, "the U.S. does not have a facility where you can operate a reactor inside a vacuum chamber," Corbisiero says.

Despite the hurdles that must be overcome, many experts are pretty jazzed about the possibility of a lunar nuclear reactor. "I'm enthusiastic about it," Middleburgh says. But the only way to know for sure that one will work, and work safely, is to go to the moon and switch it on.

LAL AT RAND is also excited about the prospect of the U.S. operating the first nuclear reactor on the moon. But she spends a lot of time thinking about "all the things NASA could do wrong" in the process. Those pitfalls include its interactions with China, a spacefaring nation also keen to establish a nuclear-powered foothold on the lunar south pole.

In one possible future scenario, China and the U.S. have their own spacious patches of the lunar south pole. They coordinate certain operations

Lockheed Martin illustrations show a potential future lunar fission power plant (*left*) and a nuclear-powered Artemis moon base (*right*).

and share a bevy of scientific discoveries, all while keeping a respectful distance from each other. "That's the best-case scenario," Lal says. But it's not the most realistic. China and the U.S. are geopolitical rivals and competitors in the new race to claim the moon. "There's new land, and it belongs to no one," Lal says. "Whoever gets there first makes the rules."

The United Nations Outer Space Treaty, which was signed in 1967, states that "outer space is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." Nobody can legally own territory on the moon (yet). But in his August 2025 declaration, Duffy noted that nuclear power plants could be used to define a "keep-out zone" to other parties: *Hey, this is sensitive, dangerous equipment—stay away!*

Establishing a base would also grant a nation de facto control over a given patch of the moon. But nuclear power plants can be put anywhere for any purpose, far from any astronauts, so both China and the U.S. could place them like radioactive flags. Nations could quickly stake not quite legal claims on any land they deemed valuable—including any swaths rich in water.

For that reason, "we don't want to *not* be the first to have a nuclear reactor on the moon," Lal says. "The U.S. should be the first to land, to set the norms." Preferably, these norms would include the nonaggressive placement of safely designed nuclear reactors. The deployment of each reactor should also be clearly communicated ahead of time to our neighbors on the lunar surface. "We need to be able to talk to our friends *and* adversaries," she says.

But in the current political climate, clandestine behaviors could win out. Suspicion is a breeding ground for unforced errors. And if things get confrontational, nuclear power plants may not be the only territorial markers spacefaring nations put down. "If they want to put a nuclear weapon on the moon, they will just do it," Lal says. Putting nukes in space is illegal under the Outer Space Treaty. Nevertheless, Russia is thought to be developing one for this very purpose. And the treaty isn't legally enforceable; it's more like a guideline. "If somebody wants to be nefarious, there is no way [to force] them not to be," she adds.

For a moment, though, let's envision a future in which someone sets up a lunar base that's safely powered by the first-ever nuclear reactor on the moon. Forget a cramped shoebox; they can now create and sustain a small village for their moonwalkers. In time, this base becomes an engineering hub and a fuel depot—a springboard for astronauts to reach the ocher-hued planet farther afield.

America wants to realize this dream first. So does China. Let's hope that in their scramble to win, they unfurl their nuclear ambitions carefully. "Some overconservatism at the very beginning of the lunar nuclear endeavor is required," Middleburgh says. No matter how exciting the prospect is and what it may enable, one question should be on everyone's mind throughout: "What happens if it goes wrong?" ●

FROM OUR ARCHIVES
Back to the Moon. Sarah Scoles; October 2024. Scientific American.com/archive

Lockheed Martin

What's Wrong with Quantum Mechanics

A 100-year-old theory might explain the confusion

BY TIM FOLGER

QUANTUM MECHANICS IS BOTH THE MOST powerful theory physicists have ever devised and the most baffling. On the one hand, countless experiments have confirmed its predictions; the theory undergirds modern technology and makes possible the electronic devices we use every day. On the other hand, quantum mechanics describes an underlying reality that is utterly at odds with the world we perceive. In the quantum realm, a single particle exists in many places at once—at least while no one is looking at it. The theory also allows for inexplicable connectedness: a pair of atoms can be "entangled" such that no matter how far apart they are, whatever happens to one atom instantaneously affects the other. Albert Einstein called the phenomenon "spooky action at a distance."

These paradoxes have defined—or plagued—the theory since its inception more than a century ago. To this day, physicists still don't agree on what quantum mechanics is telling us about the nature of reality. Are there multiple universes? Do things come into existence only when they're observed? Is consciousness somehow central to the laws of physics? And what if all these mysteries could have been resolved right at the birth of quantum mechanics?

That's the case Antony Valentini, a physicist at Imperial College London, makes in his newest book, *Beyond the Quantum: A Quest for the Origin and Hidden Meaning of Quantum Mechanics* (Oxford University Press, 2026).

Tim Folger is a freelance journalist who writes for *National Geographic*, *Discover*, and other national publications.

Valentini argues that Louis de Broglie, a French physicist and Nobel laureate, developed a framework for quantum mechanics around 100 years ago that eliminated its paradoxes. In pilot wave theory, as de Broglie's brainchild is known, particles are guided by attendant waves. The particles themselves are always in one position and one position only; it is the spatially extended pilot wave that creates the impression that a particle is at once here and there. There's no need for an observer to conjure that particle into being. Even though de Broglie's 1924 conjecture about the wavelike nature of matter was quickly confirmed by experiment and became integral to quantum theory, the physics community discounted or misrepresented the larger ideas from which he derived his key insights.

Valentini has spent his entire career championing de Broglie's views. He recently spoke to SCIENTIFIC AMERICAN about de Broglie's lonely path and why he might have been on to something. *An edited transcript of the interview follows.*

In the history of science, has there ever been another situation where there were such wildly divergent views about what a theory means?

I'm not sure there has. If you go back to the time of Isaac Newton, he thought that space was empty and that there was a direct gravitational action at a distance. And on the Continent there were the Cartesians [followers of mathematician and philosopher René Descartes], who thought, "Oh, no, space is full of this material medium, and that explains gravitational attraction." But the debate didn't last all that long. Certainly in the quantum case, the sheer variety of interpretations that say such completely different things about the world—I think it's a pretty safe bet that there's no analogue in the history of science.

One of the most striking things about modern physics is the stark divide between the macroscopic and quan-

Continued on page 79

Illustration by Shideh Ghandeharizadeh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Continued from page 78

tum worlds, which seem to be governed by entirely different physical laws. You liken this situation to the way medieval astronomers split the cosmos into earthly and celestial regions.

I think it's a useful and valid parallel, this idea that there was a heavenly realm that we couldn't understand; anything beyond the moon was eternal and unchanging, completely different from the sublunar world, which was made of ordinary, imperfect matter that was always changing. It's a distinction that goes back to Aristotle. The parallel with quantum mechanics is extraordinary, that the quantum system is something our mind can't understand. We can understand only the macroscopic one.

Austrian physicist Erwin Schrödinger developed quantum theory's wave equation, which describes quantum systems as waves that evolve with time. What role did this equation play in the so-called measurement problem: If a particle exists in different places at once, why do measurements find any given particle in only a single location?

Schrödinger created the measurement problem by removing the particles from de Broglie's theory. Mathematically, a quantum wave is a superposition of many different positions: a particle can be here and here and here; it can be anywhere. You can have a superposition of a live cat and a dead cat or a superposition of different energies. They're all just different variations on the same theme. The wave equation contains all possible positions. How can you then explain why we see this little pointlike object if the only reality is an extended wave?

And this conundrum was recognized early in the development of quantum theory.

Here's Wolfgang Pauli writing to Niels Bohr in 1927: "In the last issue of the *Journal de Physique,* a paper by de Broglie has appeared.... It is very rich in ideas and very sharp, and on a much higher level than the childish papers by Schrödinger, who even today still thinks he may ... abolish material points." And because Schrödinger removed particles from his equation, we've ended up with decades of confusion.

> "It's as if people are stuck on repeat—the same wrong arguments just go around and around and around."
>
> —ANTONY VALENTINI *IMPERIAL COLLEGE LONDON*

Why do you think de Broglie's theory was set aside and neglected?

I'm not sure there is one simple answer. It's maybe a mix of reasons. In 1923 de Broglie had developed a new theory of motion. It was a complete break, very different from Newtonian or even Einsteinian physics. And yet it completely passed people by. The only thing that entered the collective consciousness of physicists was that de Broglie had shown that a particle can behave like a wave.

Word of de Broglie's thesis spread, although hardly anyone actually read it. Einstein did. It was Einstein who really alerted people that de Broglie had done something very important. He encouraged Schrödinger to read it—and he read it. Most other people, it seems, never read de Broglie's thesis.

And then there is the sociological factor—de Broglie was quite isolated in Paris. He was a bit of a loner; he worked essentially by himself. At that time, in the 1920s, France was really a backwater in theoretical physics. It was strong in experimental physics and strong in mathematics but not in theoretical physics.

Has your pursuit of pilot wave theory been a lonely one? Rewarding? Frustrating?

The short answer is all of that and more. Lonely? It's been this peculiar situation. I've really tried to get the key points across to physicists. It just seems to get brushed aside. It's as if people are stuck on repeat—the same wrong arguments, the same historical misconceptions just go around and around and around.

When I first came across pilot wave theory, it seemed to me so obvious. Oh, my God, pilot wave theory in principle is a wider physics; quantum theory is a special case of something bigger. Pilot wave theory has exciting new physics, and maybe we can find evidence for it.

In your book, you describe how pilot wave theory's predictions about the physics of matter differ in some cases from the predictions of accepted quantum mechanics. In particular, you mention how the cosmic microwave background (CMB)—the radiation created during the big bang that now permeates the universe—might support some of the predictions of pilot wave theory.

The CMB is an excellent and promising avenue, and I've done a lot of work on that with various collaborators. There are reported anomalies in the CMB that qualitatively match the kind of anomalies pilot wave theory would predict. There are some tantalizing hints, but the data are just too noisy to draw any firm conclusions from. This matter probably won't be settled for another 10 years or so.

Is pilot wave theory true? Is it an accurate theory of the world? If I knew it was true, I wouldn't be researching it. There's always, in the back of my mind, the thought that this could all be completely wrong! Or it could be that it's kind of partly right. In the late 19th century Ludwig Boltzmann modeled gas molecules as little billiard balls—little hard spheres that are bouncing around. It turns out that molecules are much more complicated than that. But still, his model contained a lot of truth. It might be that pilot wave theory is a bit like that, an approximate model. ●

The Ethics of AI Art

When people understand AI-generated art's underlying system and process, its moral implications become harder to accept

BY IONELA BARA

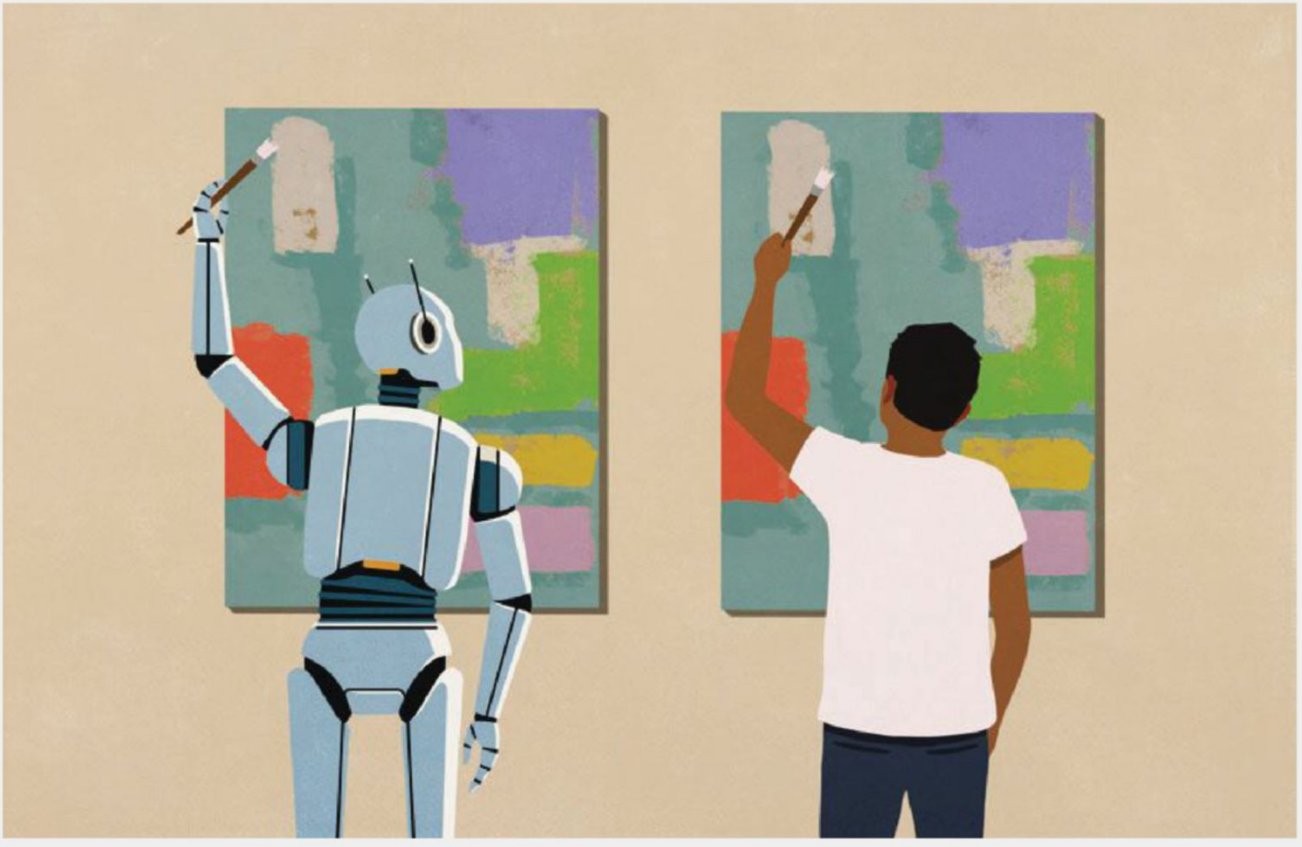
IN EARLY 2025 AUCTION HOUSE Christie's in New York City sold an unusual collection of art pieces. Surreal portraits, photorealistic images and cartoon-inspired creations, all generated by artificial intelligence, raked in more than $700,000, beating sale estimates. The first-of-its-kind event also sparked a backlash. More than 6,000 artists protested that the AI models used to create these works had been trained on copyrighted images without creator consent. Although the auction house had argued that the works demonstrated "human agency in the age of AI," critics saw the event as an example of an industry rushing to commercialize technology built on uncompensated creative labor.

Other artistic and professional communities have also been worried. A report released last November found that more than half of novelists surveyed in the U.K. thought AI could end their career. Many authors believed that their work had already been used without consent to train large language models and that AI was flooding the market with low-quality prose. Audiences seem to have complicated feelings about the technology, too. As one survey found, many Americans are okay with AI as a tool for creative professionals but not as a replacement for their work.

A viewer's comfort with AI art, however, may depend on how much they know about the way it was made. I study neuroaesthetics, a field that combines neuroscience, psychology, and our perception of beauty and art. My colleagues and I have found that the more people learn about how AI's back end works—the datasets, training process and prompting—the less comfortable they are with the moral considerations surrounding these creations and the value of AI-generated pieces.

I became curious about AI because

Ionela Bara is a postdoctoral researcher and lecturer in the Social Brain Sciences laboratory at ETH Zurich. She studies the cognitive and neural bases of aesthetic experience and the ways that people perceive, evaluate and engage with visual art.



Malte Mueller/Getty Images

its rapid proliferation in the art world has started to expose a gap between what the technology is and what people know about it. Past research has shown that people tend to give AI art lower ratings on creativity, value and emotional depth. And in my own work, I had studied how knowledge about art changes the way we view it. This background led me to wonder whether knowledge about AI shapes people's judgments of AI-generated art and might help explain the often observed bias against it.

To investigate this question, my colleagues and I conducted three experiments, each involving 100 participants. We started by presenting people with AI-generated art images and asking about their morality and aesthetic value. For example, participants in two of these experiments had to rate how morally acceptable it was to use AI to produce such art, earn money or prestige from these works and label them as conventional art. People also had to rate how much they aesthetically appreciated the images we presented.

In the first experiment, we showed our participants 20 landscapes and 20 portraits that were generated with DALL-E 3 from prompts based on the Impressionist art of Spanish painter Joaquín Sorolla. To ensure that the AI-generated images were highly similar to the artist's work, we gave the AI very specific instructions. For example, one prompt was "Impressionistic painting of simple wooden Valencian fishing boats in shallow water, 1900s-style, large white sails, loose brushstrokes, Sorolla, master of light."

Half of the participants viewed this AI art with no added context. The other half received a short text that gave them more information. It read: "This image was generated by an AI algorithm that produces images from textual descriptors. To accomplish that, several steps are required. First, the AI algorithm is trained by learning a large dataset of art images and their corresponding text descriptors, such as the artist's name. Then, the AI algorithm is able to generate new images based on different textual prompts (e.g., artist's name, artistic style, whether it depicts a seascape, landscape, or people)."

The additional information made a difference. When people knew how the AI system operated, they perceived the images it produced as less morally acceptable, especially when the creation of these images involved financial gain and artistic acclaim. But the aesthetic appeal of the images did not change, suggesting that learning how AI works made people reflect on ethics, not aesthetics.

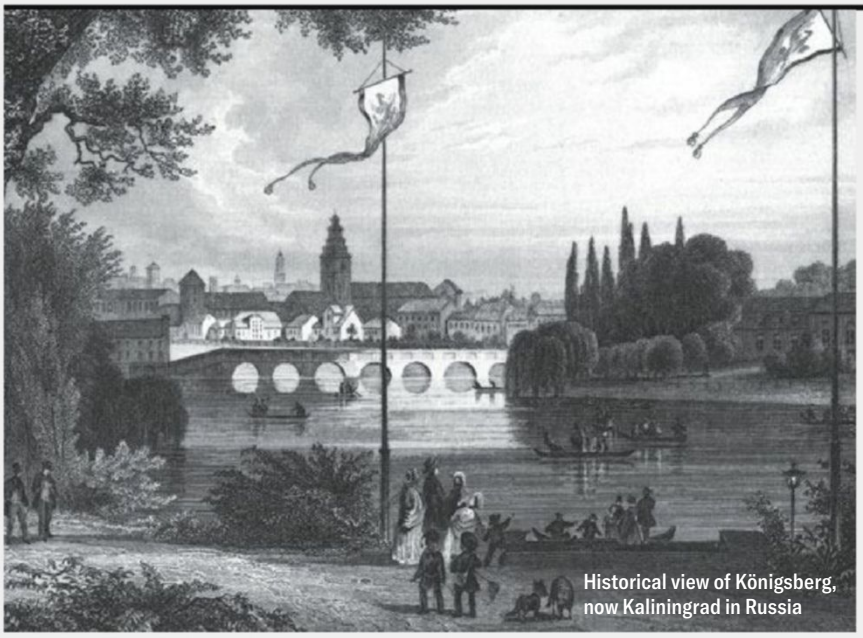
Psychologists have found that people's judgments about what is good or valuable can change when they learn something has earned awards or praise from experts. Authority bias, for example, makes us more inclined to agree with people who seem to be in charge or in the know. In addition, cues such as success or prestige can lead people to see something as more morally good. In our second study, we told participants that some of the AI art had been exhibited, sold or praised. But we were surprised to find that sharing a work's success did not improve the moral acceptability of the image in the eyes of people who had learned about how the art was created.

In a final experiment, we tested people's automatic judgments of AI-made versus human-made art. We used a tool from psychology called a go/no-go association task, in which people are asked to very quickly link one kind of prompt, such as an image, with another, such as the word "good" or "bad." In this experiment, we showed participants images of Impressionist paintings (which were either AI-generated or human-created) along with object-category labels on the left ("AI art" or "human art") and attribute labels on the right (such as "good" or "bad"). Participants needed to click a button if the image and labels were in alignment and to refrain from responding if they were not. This task needed to be done quickly and over many trials as a way to capture the most immediate associations. We worked with people who had not been given any additional education on AI to try to get a sense of what the average person might think.

We found no strong automatic tendency to see AI or human art as inherently better or worse. This finding tells us that people don't yet have a knee-jerk reaction or deeply held opinion about AI art as opposed to that made by humans. It also underscores that, as our earlier experiments suggested, moral resistance to AI art is something people learn over time.

People don't yet have a knee-jerk reaction to AI art. Moral resistance is something they learn over time.

Overall, when people know how AI operates, they become more careful in judging its moral fairness. This finding suggests that educating audiences, artists, curators and policymakers about how technology works could shape the future of the technology in the art world. Artists working with AI tools can help in this effort by sharing information about the models, data or prompts they used and clarifying where their own human hand guided the process. Although such transparency may lead to critiques, it might also build credibility and equip people with the tools they need to think critically about technology. ●



Historical view of Königsberg, now Kaliningrad in Russia

A Bridge-Crossing Puzzle Led to New Math

Are you smarter than an 18th-century Prussian?

BY JACK MURTAGH

DURING THE 18TH CENTURY the denizens of the Prussian city of Königsberg wrestled with a puzzle: How could they find a walking path through the city that crossed each of its storied seven bridges exactly once?

The bridges spanned a river containing two large islands. No matter how people strategized their routes, they couldn't avoid repeating a bridge.

The problem stymied local thinkers, who eventually wrote a letter to well-known Swiss mathematician Leonhard Euler (pronounced "oiler") begging him to lay their curiosity to rest. Euler responded dismissively, claiming the problem had "little relationship to mathematics." In a way, he was right because the relevant math hadn't been invented yet. Despite his initial demurral, Euler did end up solving the puzzle of the seven bridges of Königsberg, unaware that in the process he had birthed two new branches of math.

Say you were a resident of Königsberg. Looking at the map (*top on opposite page*), could you design a path that traverses every bridge once? You'd have to think like a mathematician. The first step in wrangling any math problem is to strip away extraneous information until only the essential elements remain, a process called abstraction. Many features of the map don't affect the question at hand. The lengths of the bridges, the sizes of the landmasses, even the geographic orientation of the land and bridges can all be discarded. All that matters is which pieces of land connect to which other ones and how many times. Now we can create a much simpler diagram consisting only of circles and lines to represent land and bridges, respectively (*bottom on opposite page*).

Modern math parlance calls this a graph, not to be confused with unrelated mathematical graphs such as plots in the *x*-*y* plane or bar graphs and other statistical visualizations. Perhaps "network" would have been a better term to avoid any mix-ups. We call the circles "vertices" and the lines "edges." Today graph theory is a major area of math and computer science with wide-ranging applications. Graphs don't have to represent land and bridges. They can represent social networks, protein interactions, state borders, neural networks, the World Wide Web, or any other data involving pairwise relations.

Abstraction allows mathematicians to translate a highly specific problem about a particular arrangement of bridges in an old city into a general problem about all graphs. Given a graph with any number of vertices and edges, is there a path that traverses every edge exactly once? It turns out that an amazingly simple test can answer this question for any graph: For every vertex (landmass in our current puzzle), count the number of edges (bridges) emanating from it. If all of those counts are even numbers or if all but two of them are even, then the path exists; otherwise the path is impossible.

Let's explore the reasoning. Imagine a path through a graph that crosses each edge once. Consider a vertex in the middle of that path (not the starting or ending vertex). If that vertex has many edges, then your path will visit it multiple times, but every time you enter the vertex you must also exit it via a different edge. So each time a vertex in the middle of the path gets visited, two edges get visited. That works only if every vertex in the middle of the path has an even number of edges. The start and end of the path are the only exceptions because the starting vertex doesn't have to be

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The 18th-century city map of Königsberg is a digitally enhanced reproduction that was modified to highlight the river and bridges.

entered, and the ending vertex doesn't have to be exited. So if we have exactly two vertices with an odd number of edges, then our path is possible if we start and end at those vertices. If every vertex has an even number of edges, then there will be a path that starts and ends at the same vertex, forming a loop.

This argument is considered the first result in graph theory, and paths through graphs that visit every edge once are now called Eulerian paths. Technically Euler's argument describes only the conditions that make an Eulerian path impossible, and the proof that such a path always exists under these conditions came later. Applying what we've learned to the bridges of Königsberg, we see that all four vertices have an odd number of edges emanating from them, meaning, alas, the Prussian amblers searched in vain.

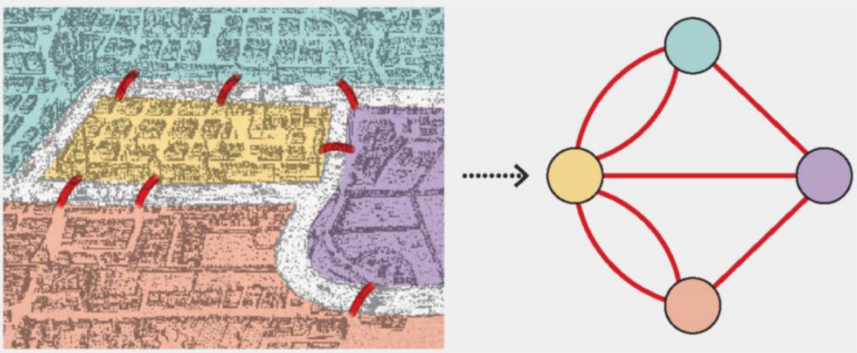
Here's a peculiar side note: Finding a path through a graph that visits every vertex (the land rather than the bridges in our example) exactly once sounds like a closely related problem, but it is actually an entirely different beast. Although a simple test can determine whether a graph contains an Eulerian path, we don't know any general, efficient procedure for this vertex-focused variant. This puzzle is called the Hamiltonian path problem, and it belongs to a class of problems widely believed to be computationally intractable.

Although Euler initially sneered at the bridge problem, he was ultimately drawn in by his inability to solve it with his usual tool kit. He wrote to a friend: "This question is so banal but seemed to me worthy of attention in that neither geometry, nor algebra, nor even the art of counting was sufficient to solve it." At the time, geometry concerned quantitative notions such as distance, angle and area. The bridge problem appeared geometric in nature, but it didn't call for any kind of measurement. The problem required a new abstraction that ignored traditional geometric quantities while respecting the pairwise connections at the heart of the question.

The idea to reduce the map of Königsberg to a bare-bones graph might seem obvious in retrospect, but many of the best abstractions do. The history of math tells the story of the power of abstraction. If ancient mathematical minds had quantitative questions about oranges, pearls or even Earth, they could develop bespoke language and techniques for tackling each new challenge. But the endeavor becomes so much easier and clearer once one recognizes that these disparate-seeming objects all instantiate the same higher-order entity: a sphere. Giving the abstraction a name and a definition allows people who have never even met to build on one another's work without reinventing the wheel.

Euler's paper not only launched the field of graph theory but also sowed the seeds for another major branch of math called topology. Topology is the study of geometric properties that persist even when we stretch, compress or deform objects as though they were made of highly elastic rubber. So we have one level of abstraction that takes us from real-world objects such as oranges, mountains and dice to their shapes (spheres, pyramids and cubes), and topology introduces a second level of abstraction in which we view spheres, pyramids and cubes as instantiations of some even higher-order entity. Topologists view these solids as equivalent because they can each be molded into the others in a rubbery world, unlike a doughnut, which would maintain a hole no matter how you stretched it.

By abstracting away the quantitative particulars in the map of Königsberg, Euler opened the door to a new kind of geometric thinking unmoored from the quantitative particulars of distance and angle that had dominated the subject for millennia. Graph theory and topology continue to yield new mathematical insights today, and we have a bygone civilization of saunterers to thank. ●



Alamy Stock Photo (*maps*); Amanda Montañez (*highlighting* and *diagram*)

Apparent strike damage at Iran's naval base in Konarak on March 1 was captured by a commercial satellite.

Planet Labs PBC

War in Plain Sight

Near-real-time satellite coverage means militaries can no longer hide. So they are learning to lie better

BY SARAH SCOLES

THE DAY AFTER THE U.S. AND ISRAEL BEGAN THE current war with Iran, satellite company Planet Labs e-mailed a media release. "Sharing our first batch of areas impacted by airstrikes," it read. Planet operates a constellation of about 200 satellites that together can take pictures of much of Earth—including the parts in turmoil—daily. The release included a link to images taken that day of collapsed tunnels at a missile base and smoke over a naval facility.

As Planet's message illustrates, governments, journalists and ordinary observers alike can now see what is happening across the globe soon after it happens, thanks to infrastructure in space. This relatively new ability is a result of the proliferation of "remote-sensing" satellites like Planet's, which look down at Earth constantly.

Planet's hundreds of remote-sensing spacecraft share the sky with hundreds more, and together they're pushing society toward what has been called the GEOINT singularity: a time when geospatial intelligence will be available in real time to the average person, who will be able to see not just what the world looks like but how it is changing. The world hasn't quite reached that tipping point. But merely approaching it has changed warfare for good.

The U.S. government has operated spy satellites since the late 1950s, but it wasn't until 1992 that private companies got the go-ahead to operate their own. Today commercial remote-sensing satellites are ubiquitous: Igor Morić

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of Princeton University, whose research includes ways for satellites to be used in arms control, calculates that with their combined powers as a "superconstellation," they could image every spot on the planet every few hours.

Some of the sharpest eyes in the sky belong to a company called Vantor, whose satellites can resolve objects the size of a cutting board from orbit. Its 10 satellites can't cover the globe in the same way Planet's hundreds can, but they can return to high-priority spots 15 times a day and deliver pictures in as little as 15 minutes. Vantor has also used its data to make 2D and 3D maps of most of the world, updated the same day new intelligence arrives.

The U.S. and allied governments that Vantor does business with want what CEO Dan Smoot calls "their living globe"—"so they can see their world updated in real time and can see anything that's changing within that world," he says. But private satellites don't just take pictures anymore: they can detect a variety of wavelengths and carry instruments such as radar and devices that can pick up radio transmissions, presenting a rapidly refreshed view of the planet beyond what the human eye can perceive.

One company working with these nonvisual signals is HawkEye 360, which uses 30 satellites to detect and pinpoint radio transmissions. It can revisit most places every hour or so. "It's one of those modalities that you can't fully hide from," says Todd Probert, HawkEye's chief operating officer. That's particularly useful for tracking ships, something people have been interested in doing in the Strait of Hormuz, where the conflict with Iran choked off oil shipping.

Ships that want to go invisible may turn off their automated identification systems or spoof their GPS location so—magic!—they appear to be somewhere they're not. But they can't hide all their radio transmissions, such as the ones radar systems beam out. HawkEye's satellites can pick up those beams and triangulate a position—then, maybe with help from satellites that take pictures, confirm who's out there.

HawkEye's spacecraft can also sense GPS disruption, showing military officials where someone is jamming or spoofing a signal to make traditional geolocation and navigation unreliable.

With so many kinds of satellites, the prevailing logic goes, it has become much harder to conceal military activity aboveground. Going underground can obscure the action, but it's hard to wage an entire war from a bunker.

Even as Earth approaches the GEOINT singularity, truth and transparency don't always win out.

As the Planet press release shows, near-real-time satellite data allow governments to tout their destructive successes; the information also makes denials harder. In tense but nominally peaceful times, satellites can prevent escalation by easing fears of an impending attack. Morić, for instance, advocates using satellite data to verify nuclear treaties (if those continue to exist) by counting missiles in images taken from above.

But, counterintuitively, too much transparency can be dangerous, Morić cautions. Nuclear deterrence, for example, rests on the idea that both sides know they could destroy each other. But if the U.S. has up-to-the-minute information about, say, the location of China's mobile missile launchers, that visibility could undermine China's ability to retaliate in kind. And that vulnerability undercuts the logic of mutually assured destruction and paradoxically might make the use of nukes more likely.

Satellites also let countries communicate without words. Knowing that satellites were watching, Russia recently unveiled a new bomber by leaving it outside long enough for U.S. satellites to get a good look, according to Morić. But a few things in life are certain: death, taxes and militaries' desire to deceive their adversaries. So even as Earth approaches the GEOINT singularity, truth and transparency don't always win out.

For one thing, real digital images can be modified with artificial intelligence, or fake ones can be conjured out of whole cloth. Deception can also go analog: Russia and Ukraine have used fake military equipment—inflatable and wood tanks, for example—to fool sensors. Russia has also painted exact silhouettes of its bombers onto runways.

The truth, in other words, isn't so straightforward. And neither is access to it: private satellite companies are under no obligation to make their data available promptly; their decisions about when and how to do so, and to whom, make them geopolitical power players. Planet, for instance—the company that sent out the poststrike press releases early in the war with Iran—announced it would delay the release of images from some geographic areas in the Middle East for 14 days.

Planet doesn't have a monopoly on satellite imagery, and neither does the U.S., so that delay doesn't mean no one can see what's happening. But the ability to selectively limit access to ground truth can have real consequences. For instance, the *New York Times* confirmed the U.S.'s errant strike on an Iranian elementary school by using satellite imagery. Without access to those images, the world might have lived with doubt or been left to weigh the conflicting accounts of governments with every reason to spin.

Turns out, when it comes to the satellite industry and the GEOINT singularity fulfilling their ultimate promise, technology isn't the main barrier: it's humans' persistent desire to keep secrets and fool one another. ●

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SciAm.com/games

At the Same Time

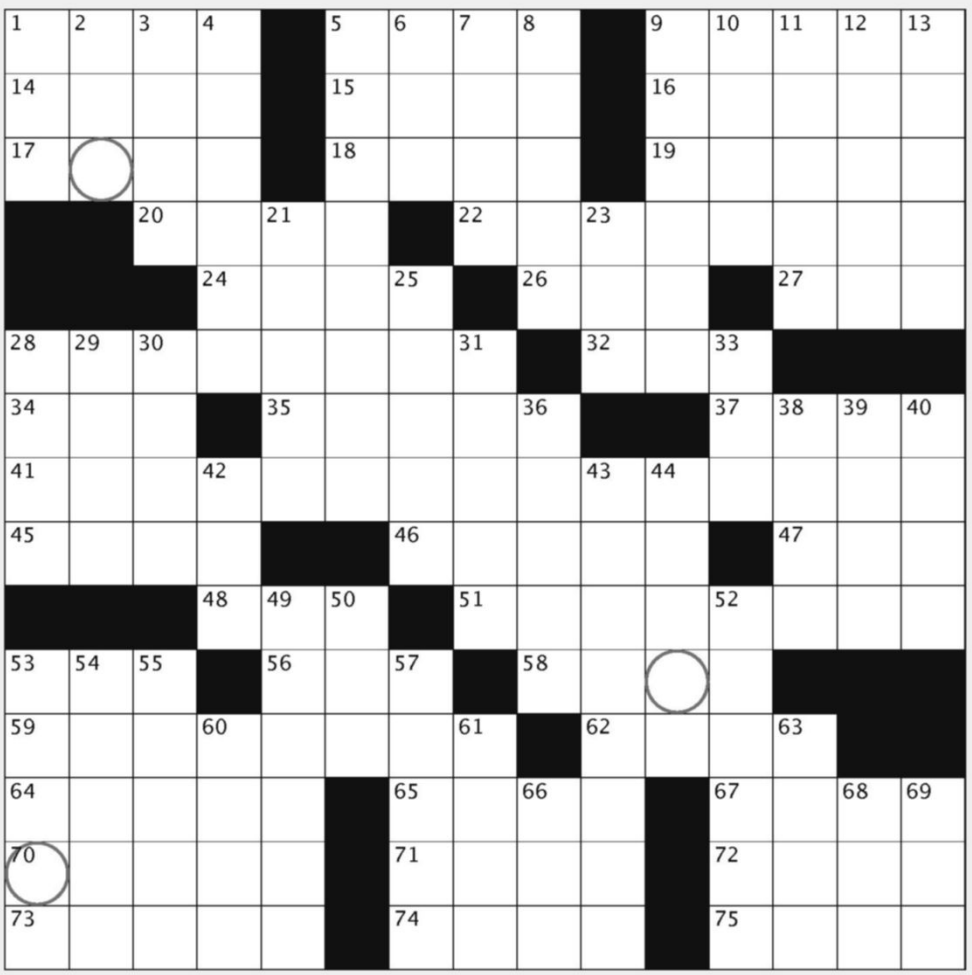
By Aimee Lucido

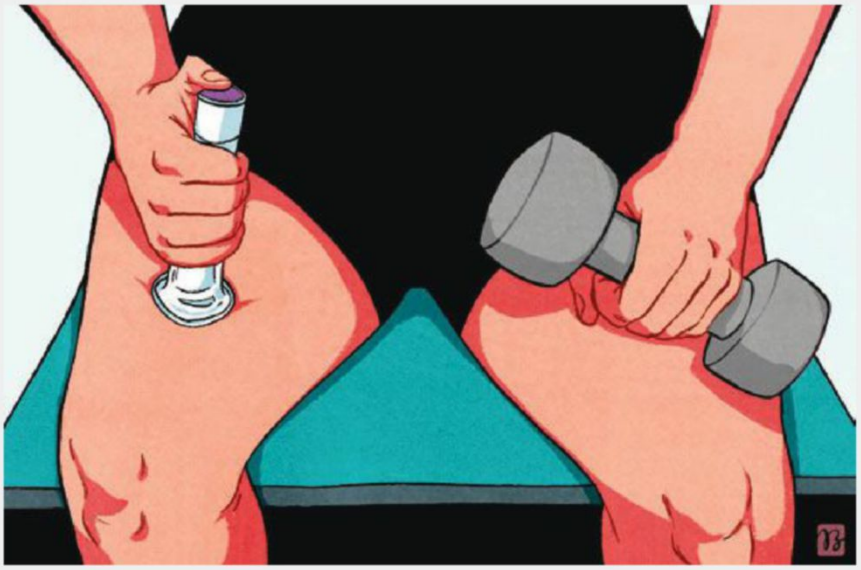
Across

1 App that takes you for a ride?
5 Orb used by certain ants to navigate (*page 19*)
9 *Via* ___ (highway long regarded as the quintessential Roman road) (*page 42*)
14 Donate
15 Field unit
16 Some *Game of Thrones* figures
17 Creature found on every continent except Antarctica
18 "The universe is a hologram," for example
19 Actress George of *Animal Kingdom*
20 Sportscaster Linda
22 Film daredevils
24 Egg-shaped tomato
26 Possible value for a qubit, simultaneously with 56-Across
27 Biodiversity-protecting law (abbr.)
28 Scrivener in a Melville tale
32 Have to repay
34 Abbr. in ancient dates
35 Falls as fish poop and debris from the ocean's surface, according to researchers (*page 20*)
37 Act gloomily
41 What you "become" while solving this puzzle because the answers to 26-Across and 56-Across can be spelled out with interchangeable letters in the three circled spaces (*page 26*)
45 Quick and nimble
46 Word before "cognition" or "metabolic rate"
47 Scot's topper
48 Male turkey
51 Florida coastal city or its county
53 Kind of deviation (abbr.)
56 Possible value for a qubit, simultaneously with 26-Across
58 One response to "Should I get bangs?"
59 Get towed by a boat for fun
62 Elevator brand featured at the Paris Exposition
64 Not available
65 Chow ___ (noodle dish)
67 Closest color to olo that humans can see without assistance
70 It's symbolic in the story of Hanukkah
71 Walk worriedly
72 Astronomer Sagan
73 Uses an intense beam of coherent monochromatic light
74 Leave fur all over
75 "Let me think . . ."

Down

1 Comfy shoe brand
2 Place to store a reminder of a past achievement
3 Emergency copter op
4 Snappy reply
5 First set of options
6 Condition of Freud's "Rat Man," in brief
7 Bauxite and galena, for two
8 "That's keen!"
9 Never before seen
10 Expert who works with both feet and meters?
11 Numeric subject of the Riemann hypothesis (*page 52*)
12 Sits at a red light
13 Eagle pose, for one
21 *The Planets* composer Gustav
23 26-Across, in Oaxaca
25 Little Boy, e.g.
28 Some summer parties, briefly
29 Repeated lyric in "Java Jive"
30 Bring up
31 Some childcare-center sites, for short
33 Bird that's canonically a goofy runner
36 "What a pity"
38 Palindromic German name
39 Fibrous substance formed from partially decomposed organic matter
40 Humorist Bombeck
42 *WSJ* competitor
43 Cast away, like Crusoe
44 Lay some cornrows, maybe
49 Initial stages
50 Goth on the big screen
52 Bit of needlework
53 Tell a long story
54 Patty Hearst alias
55 GLP-1s and others
57 Walks with difficulty
60 Tennis great Arthur
61 Two-time Emmy winner Remini
63 Fabric line
66 It's churning in Greenland
68 Octopus appendage that deposits sperm (*page 16*)
69 Type of AI that researchers taught to play Battleship (*page 17*)





New Ways to Keep Muscle as You Age

Ozempic, similar drugs and aging take off muscle. New therapies could retain it

BY LORI YOUMSHAJEKIAN

DRUGS SUCH AS WEGOVY and Ozempic can lead to profound weight loss, but fat isn't the only thing that comes off. About 25 to 40 percent of the pounds shed through these treatments is lean body mass, and that includes muscle. This undesired effect has troubled older adults who are already worried about age-related muscle loss tied to falls and bone fractures. Preserving muscle matters for young adults as well: the more you have in your 30s, the more you will retain in your 60s. Losing any amount of muscle can amplify the risk of various health issues, such as declines in physical and metabolic function.

Every weight-loss intervention—including diets, bariatric surgery and glucagonlike peptide 1 (GLP-1) receptor agonist medicine such as Wegovy—melts muscle alongside fat to some degree. Now the widespread use of GLP-1 drugs is spurring scientists to work on experimental medications that could enable weight loss that barely affects muscle at all.

Muscle offers more than physical strength. These bands of fibrous tissue are important sites for storing and metabolizing glucose or for burning it for energy. A person's muscle mass is also a strong predictor of their mobility later in life. Between our 20s and 80s we gradually lose around 30 percent of our muscle. Research suggests that GLP-1 drugs may speed up this process. Clinical trials on semaglutide (the GLP-1 sold as Wegovy and Ozempic, for example) and tirzepatide (sold as Zepbound and Mounjaro) estimate that within a few years of starting treatment, people may experience a loss of muscle mass equal to 20 years of age-related decline.

Some researchers say the amount of muscle that many people lose during GLP-1 treatment is broadly proportional to the weight lost, which isn't a health issue. But older people already have diminished muscle and have a high rate of GLP-1 prescriptions. The two factors could add up to a loss of strength and function. Plus, new research awaiting peer review suggests there is a link between GLP-1 drugs and increased risk of osteoporosis.

Drugmakers have a strong incentive to find solutions. Eli Lilly, the maker of weight-loss drug Zepbound and diabetes medication Mounjaro, is developing a muscle-retention drug called bimagrumab. It blocks myostatin, a key protein that helps to suppress muscle growth. Mutations in the gene that encodes myostatin make the protein less effective, and animals born with such changes can develop extraordinary amounts of muscle. Such mutations and unusual muscle growth have been documented in at least one human.

Myostatin binds to activin type II receptors on muscle cells, where it becomes an "off switch" that stops muscle development. Bimagrumab blocks these receptors, disabling the switch and allowing muscles to expand. And the effects might go beyond muscle. The drug also blocks the activin type II receptors on fat cells, and this action appears to reduce fat mass, says Steven Heymsfield, an obesity and body-composition expert at Pennington Biomedical Research Center in Louisiana. (He consults for Eli Lilly and has been involved in the company's bimagrumab trials.)

In a phase 2 clinical trial funded by Eli Lilly and published in *Nature Medicine,* a team of scientists, led by Heymsfield, found that combining bimagrumab with semaglutide resulted in a 22 percent reduction in body weight over 72 weeks. But 92 percent of the weight lost was fat, compared with 76 percent of that lost on semaglutide alone. People taking bima-

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Illustration by Jay Bendt

grumab not only maintained more muscle than those receiving semaglutide by itself, they actually grew new fibers. And people who took both drugs had the highest gains in grip strength.

Yet not all the evidence is favorable. In early trials of bimagrumab, older adults did develop more muscle but didn't show meaningful improvements in grip strength, walking speed or endurance. This outcome could suggest that the drug "is just making the muscle bigger without the metabolic and physical function benefits," says Dimitris Papamargaritis, an obesity researcher at the University of Leicester in England. Additional studies with tirzepatide and bimagrumab are underway.

Researchers are also pursuing another group of experimental muscle-retention drugs called SARMs, or selective androgen-receptor modulators. These synthetic compounds are designed to activate the body's androgen receptors in a manner similar to testosterone, a hormone that can trigger muscle growth. Testosterone acts throughout the body, possibly creating bad side effects for organs such as the heart and the prostate. But SARMs are engineered to act primarily in muscle and bone, potentially promoting muscle growth with fewer side effects than testosterone. A 2025 review showed that SARMs are correlated with improvements in physical performance and body composition, but their safety profile is still unclear.

Until these new medications are shown to be safe and effective in more human trials, resistance exercise and proper protein intake are the most evidence-backed ways to protect muscle, says Ian Neeland, a cardiologist and obesity expert at Case Western Reserve University. "The vast majority of older adults can tolerate [GLP-1] medications just fine," he says, but for those taking the drugs, Neeland recommends roughly 1.2 to 1.6 grams of protein per kilogram of body weight per day, about double the usual recommendation. He also says patients should engage in resistance training for about a third of their overall exercise time. ●

HORSESHOE CRAB

An alien's bumper car with strange bulging eyes
but no anti-gravity plasma engine,
just ten unseen spidery legs

that have churned the seas for eons
before we named it the horseshoe crab
in a failure of imagination.

Its fierce-looking sword is a rudder.
Not knowing you shouldn't use it to pick one up,
I did, once, but luckily it swam off unscathed.

It lays soft blobs of pale green eggs
that feed ravenous red knots,
and its bright blue blood flags germs.

Survivor of two mass extinctions,
unchanged for 250 million years,
Limulus polyphemus can't be improved.

Once I caught their mating. Hundreds stormed
the shallows of a high-tide beach,
two or three males clinging to each female.

Mesmerized by that full-moon spring orgy,
I laughed, stupidly
unreasonably happy.

Henry Stimpson writes poetry and nonfiction in Wayland, Mass., where he also sings in a rock chorus, roots for the Boston Celtics and serves as a volunteer ESOL tutor. His first collection of poems, *Divine Details,* will be published later this year by Kelsay Books.

Illustration by Masha Foya

Light trails from satellites in low-Earth orbit fill the sky in this composite long-exposure photograph, which was captured over a 30-minute period.

Alan Dyer/VWPics/Alamy

Unchecked Megaconstellations

Satellite swarms could destroy our view of the heavens and seriously damage our planet

BY PHIL PLAIT

I REMEMBER THE FIRST TIME I SAW A SATELLITE. I was a teenager, standing in my mildly light-polluted suburban yard and doing my usual stargazing. The satellite was a faint "star" moving slowly and smoothly across the sky, and as I watched it I felt a mix of awe and wonder that such a thing could be seen—and that humans could put an object into orbit at all.

That was a lifetime ago, and I now look back on that evening with more discomfiture than nostalgia; my adolescent naivete feels almost embarrassing.

That's because these days, seeing one of those celestial travelers fills me with dread. We are firmly in the era of the satellite constellation—groups of dozens of similar satellites—and are currently entering the era of the megaconstellation, wherein groups of thousands of satellites swarm the skies. The clusters of satellites started small, but like a viral outbreak, they grew almost without us noticing—and now we're dealing with a pandemic.

I wrote about this problem for *Scientific American* in May 2023. At the time, there were 7,500 active satellites orbiting Earth; about 4,000 of them were SpaceX Starlink satellites that provided Internet service. In the three years or so since then, the number of Starlink satellites in orbit has surpassed 10,000. Today there are more Starlink satellites up there than the sum total of all other operational satellites.

This ratio will almost certainly get more skewed toward Starlink, too; back in 2019, when the first Starlink satellites were launched, SpaceX filed proposals with the Federal Communications Commission for up to 30,000 additional satellites.

Does that sound bad? Well, there may come a day, all too soon, when we're nostalgic for that small a number of satellites cluttering the sky. On January 30, 2026, SpaceX applied for permission to launch as many as one million more satellites.

Yes, one million.

SpaceX's plan is for this sprawling megaconstellation to become a distributed network operating as an orbital data center, similar to ground-based data centers that provide the information-processing backbone of the Internet. In this case, instead of having equipment capable of all that processing power stored in massive warehouses, each satellite in orbit would do a small part of the number crunching and then beam the final results back to the ground.

In principle, such plans could ease the insatiable power demands and environmental effects of ground-based centers. In 2023 data centers in the U.S. alone consumed a staggering 176 million megawatt-hours of energy—a little more than 4 percent of the nation's annual electricity usage and enough to power 16 million homes for a year. Many of these centers are powered by fossil fuels, which add greenhouse gases that worsen global warming into the atmosphere. These centers also need to be cooled, and that process typ-

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ically requires vast amounts of water. And as the use of computationally intensive artificial intelligence soars, so, too, will the appetite for ever more power—and the potential for ever greater environmental harm.

Exporting most of that "compute" to orbit, SpaceX claims, is the way to break this vicious cycle. And there is some truth to that: The satellites will be solar-powered, easing the electricity demand on Earth. They won't need water to cool their hot chips and will instead rely on large radiators to vent heat—a slower, less efficient method but the best one available in the near vacuum of space. Currently in-use Starlink satellites cool themselves this way, and the heat load for a satellite used to process data would be roughly the same as for one used to provide access to the Internet, so this problem isn't the showstopper many people assume it to be.

So if you don't look too deep, large-scale orbital data centers might make sense. Scratching the surface of this idea, however, shows just how colossally terrible it is.

First, those satellites need to get to space. As astrophysicist Jonathan McDowell, my friend and colleague, points out, SpaceX claims that its Starship rocket will (once it passes testing) be able to take 150 metric tons to low-Earth orbit, but there are good reasons to think the real operational capacity will be more like 100 metric tons. Assuming that low-Earth orbit is in fact where all the satellites will go (although many will undoubtedly need to fly higher) and that each satellite weighs two metric tons, Starship can launch around 50 of them at a time—so creating this megaconstellation even under optimized conditions would require some 20,000 Starship launches.

It gets worse: These satellites will fail after a few years and will need to be replaced. In the end, upkeep for this notional million-satellite megaconstellation could take on the order of 10 Starship launches per day—forever.

The environmental consequences wouldn't be trivial. A single Starship launch emits the equivalent of 76,000 metric tons of carbon dioxide, for example—leaving aside issues of noise pollution and potential damage to nearby habitats. Twenty thousand launches would have an immense effect, including more damage to our critical ozone layer. The fiery atmospheric reentries of satellites would be a source of pollution, too, dumping significant amounts of vaporized metal and plastic into our planet's fragile upper atmosphere. At least one Starlink satellite is already burning up in this way every day, based on when these satellites started entering orbit and their planned replacement cycles—and orbital data centers could make this reentry rate skyrocket.

As if these things weren't enough, the proliferation of megaconstellations also carries risks for the orbital environment itself. The volume of satellites already overhead is huge, but the numbers of proposed satellites are so vast that space-traffic management to avoid collisions would become an even more massive task. A single collision in orbit can become catastrophic: These satellites are moving at speeds many times faster than a rifle bullet, and a direct hit from one creates a cloud of shrapnel. That debris spreads, hitting other satellites and creating even more debris, resulting in a violent cascade called the Kessler syndrome. Triggering this sequence of events is already a real concern, despite orbital decay naturally "cleaning" low-Earth orbit over time. Increasing the numbers of satellites by several thousandfold could make this threat apocalyptically worse.

And as an astronomer, I can't help but worry over the effect on my beloved field. A study published last December in *Nature* showed that if there were roughly half a million satellites in orbit, at least one would contaminate essentially every observation taken by the Hubble Space Telescope. Ground-based telescopes are already being severely affected. Vaporized debris from reentries will also add to sky glow, making it more difficult to see faint cosmic objects. Even simple stargazing from your backyard would be hindered. In a very real sense, by launching so many satellites, we risk losing the sky.

Keep in mind that SpaceX is not the only satellite maker crowding the sky. China has filed to launch 200,000 satellites for its own network. Other countries and companies will no doubt follow suit; Amazon and Blue Origin already plan on launching thousands of satellites each. Even more concerning is a new company called Reflect Orbital that wants to launch thousands of giant space mirrors into orbit to provide "sunlight on demand" anywhere on Earth. The beams would be far brighter than the full moon and, even if carefully pointed, would scatter in the atmosphere to be very bright off-beam, disrupting wildlife and effectively destroying the sky's remaining natural beauty by erasing the stars from our sight. These mirrors are a truly terrible idea.

In three years the number of Starlink satellites in orbit has gone from about 4,000 to more than 10,000.

That's the common theme here, in fact. Even if we ignore the deeply disturbing environmental and light pollution from all these launches and reentries, there is another consequence. Our night sky—and it is ours—is a natural wonder, a cosmic park we need to preserve, not commodify with a laissez-faire attitude. This careless exploitation of the heavens above is a real danger to us all. ●

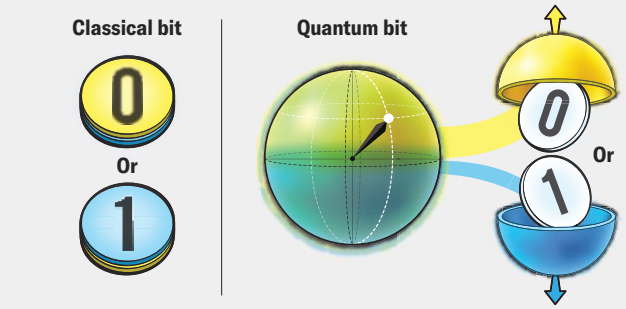
A Qubit Field Guide

Scientists are exploring many different platforms for quantum computers

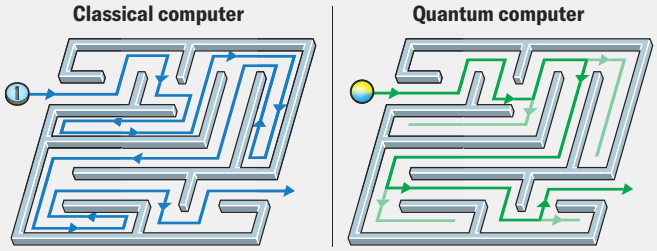
TEXT BY CLARA MOSKOWITZ
GRAPHICS BY BEN GILLILAND AND AMANDA HOBBS

AROUND THE WORLD researchers are racing to build computers that take advantage of the bizarre rules of quantum mechanics. Such machines could perform calculations impossible for conventional computers and solve certain problems much more quickly.

The magic of quantum computers comes from their quantum bits, or qubits. Classical computer bits can occupy one of two states: 0 and 1. Quantum bits, however, can be placed in a weird state called a superposition, where they simultaneously occupy some combination of 0 and 1. Qubits, therefore, can take on an infinite number of possible states akin to the infinite points on the surface of a sphere. Qubits can also experience entanglement—a special quantum connection that enables operations on one qubit to affect another qubit.



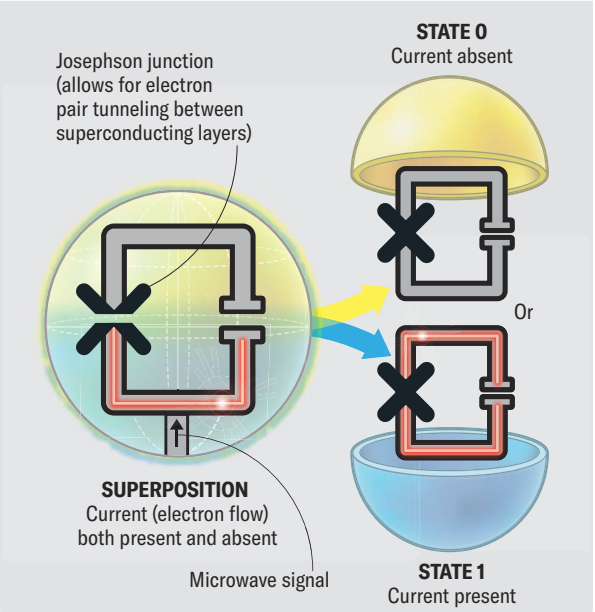
These abilities enable their special feats of computing. Imagine that a classical computer solves a maze by trying one path at a time. Quantum computers, in contrast, can essentially explore all possible routes at once. When scientists measure a qubit, however, its limitless possibilities collapse into a single option.



But what exactly is a qubit? Qubits can be encoded in many different physical systems, and researchers are still pursuing multiple alternatives. “It is a completely wide-open space right now,” says quantum computing scientist Nathalie de Leon of Princeton University, who is also a visiting research faculty member at Google Quantum AI. “All of these platforms still have open science questions in addition to engineering and scaling risk.” Here are some of the options.

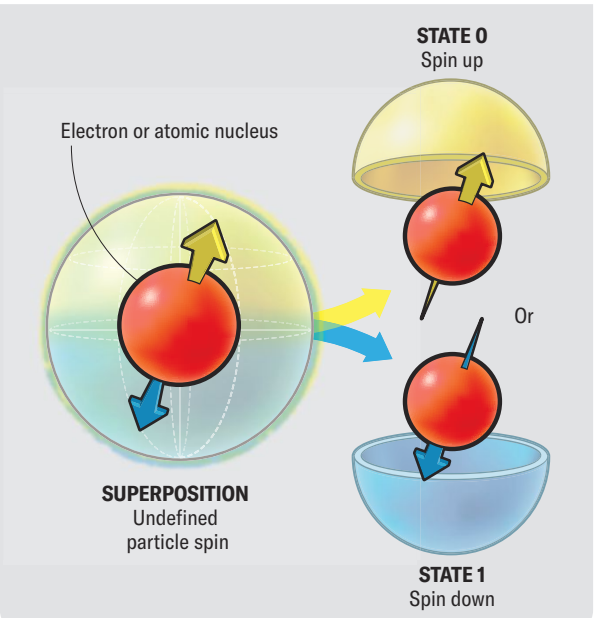
SUPERCONDUCTING QUBITS

Superconducting qubits are made of tiny circuits of materials that conduct electricity with zero resistance at ultracold temperatures. The energy level of the circuit determines a qubit’s state: when the circuit absorbs a microwave photon, the qubit jumps from the ground state (0) to the first excited state (1). Some scientists favor these qubits because they can perform operations very quickly.



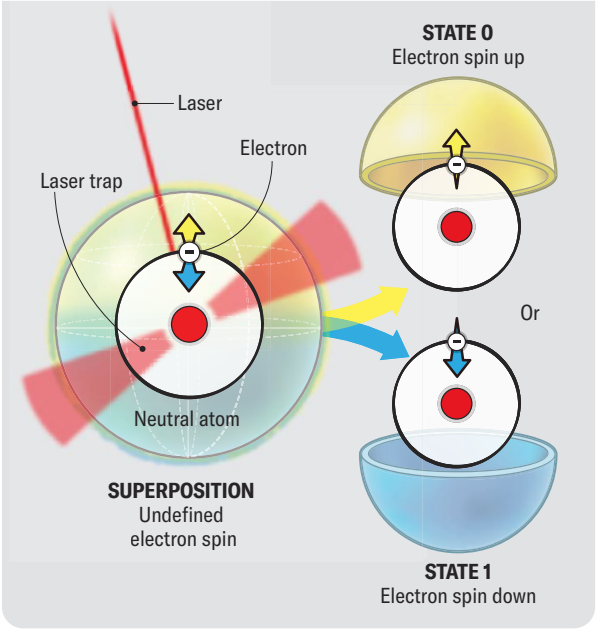
SOLID-STATE SPIN QUBITS

These qubits are based on the spin state of single particles. They include electrons in semiconductors confined by electrostatic traps, electrons and nuclear spins associated with atomic defects in semiconductors, electrons floating on liquid helium, and defect centers in wide-bandgap materials. Chips made with them can be wired using the same technology used in classical semiconductors.



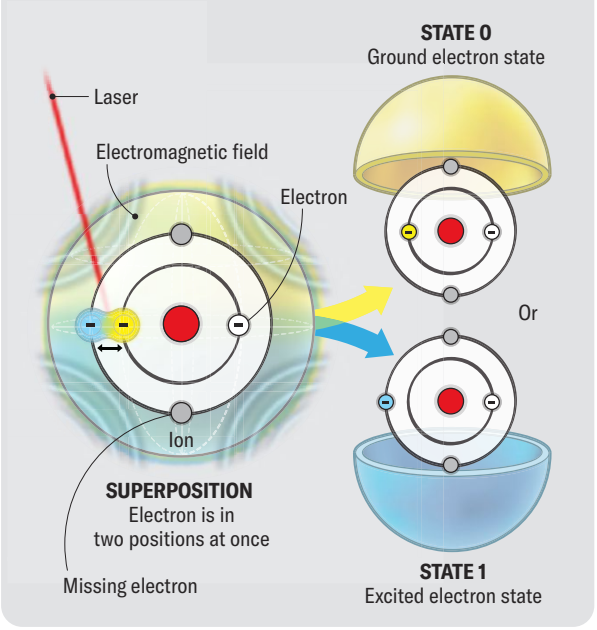
NEUTRAL ATOMS

These atoms have no net electric charge. Scientists can make them into qubits by using lasers to trap, manipulate and read them. Their state is determined by the spin of the electron or the spin of the atomic nucleus. They are prized by some researchers for the ease with which they can be combined to scale up into large numbers of qubits.



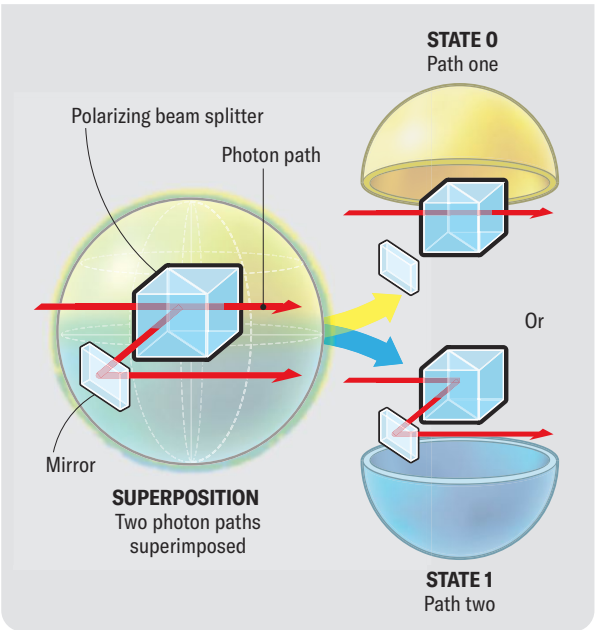
TRAPPED IONS

These qubits use the spin states of individual ions (charged atoms) that scientists hold in place with electromagnetic fields and manipulate with lasers. The atoms may be, for example, calcium, magnesium or beryllium. Some early experiments used orbital positions of electrons as qubit states, as shown below. They have demonstrated the lowest error rates for gates between qubits.



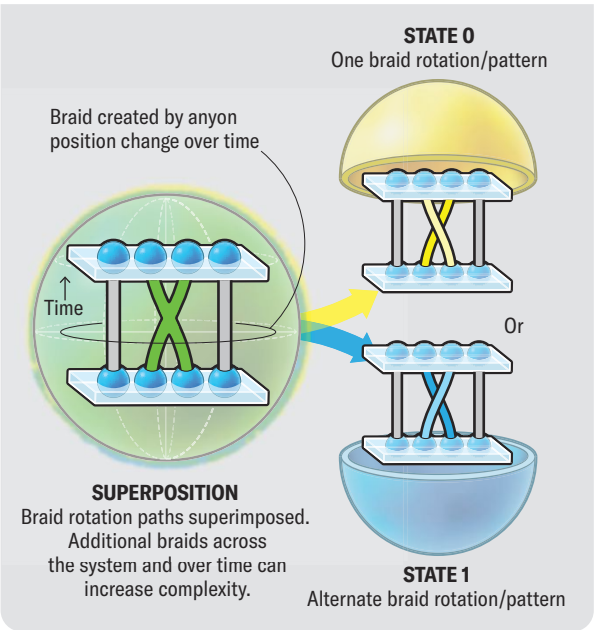
PHOTONIC QUBITS

These qubits are made of particles of light, called photons, and their state is encoded in the direction of the photon's travel along a spatial pathway called a rail. One advantage of them is that they can be scaled up into larger and larger computers by means of the same techniques that helped to scale up classical optical and electronic chips.



TOPOLOGICAL QUBITS

Instead of using circuits or individual atoms, topological qubits are made of quasiparticles called anyons. They are theorized to be less error prone than other types of qubits, but scientists are still working on demonstrating them experimentally.



Source: "The Qubit," by Massine Kelai/Center for Quantum Nanoscience (https://qns.science/thequbit) (*maze concept reference*)

50, 100 & 150 Years

AN ELECTRON-HOLE LIQUID

1976 "Recently scientists have discovered that the carriers of electric charge inside a crystal can exist in a state that has many of the properties associated with water. For instance, it can exist as a vapor, and when the relative humidity becomes high enough, the particles condense. Unlike water, the new liquid exists only inside a solid semiconductor, and it cannot be extracted from that environment. Instead of the atoms or molecules of an ordinary liquid, it consists of electrons and 'holes,' or the positively charged voids formed by the absence of an electron. The electrons and holes continually annihilate each other and, in the process, give off infrared radiation. As a result, the liquid is inherently unstable; it disappears in a fraction of a second without a continual supply of electrons and holes.

"Finally, the new liquid is essentially a quantum-mechanical fluid. Effects that are negligible in conventional fluids have a major influence on the electron-hole liquid. For these reasons the new liquid offers a unique testing ground for some of the fundamental principles of physics."

HOW TO OBSERVE SUNSPOTS

1926 "For the last year or two, the number of sunspots has been rapidly increasing, as well as their size. It is not unusual for a spot, or spot group, to be large enough to be seen with the unaided eye. 'Unaided' is rather a misnomer, for no sane man would think of looking at the sun without some protective device, either the old-fashioned smoked glass or the more modern piece of densely fogged film. With this simple equipment, the amateur may see the spots and observe their stately progress across the sun's disk from day to day as the rotation carries them onward."

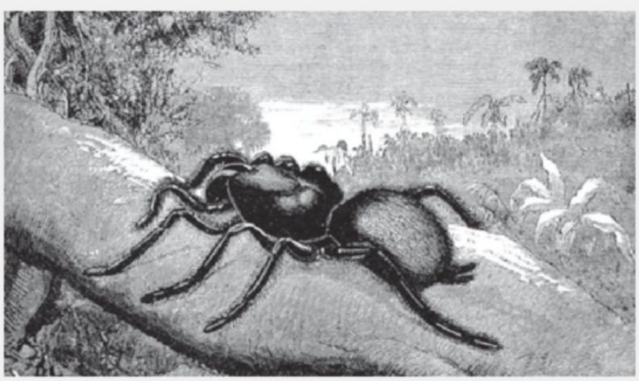
IS EARTH'S INTERIOR MOLTEN?

"Man has never been able to penetrate much more than one mile beneath Earth's surface—a mere pinprick. Yet, while science does not claim positive assurance regarding the actual conditions in Earth's inner layers, there are certain things about it which we know are not so. One is that Earth's interior is a molten liquid. Probably nothing has tended so strongly to crystallize this widespread misconception as the existence of volcanoes, pouring out liquid lava. In Earth's center, however, the pressure is too great for the rocks to melt. Thus, they are as rigid as steel. Seismologists can easily prove the latter statement, for they record earthquake shocks that travel through Earth's interior; the characteristics of these shocks prove the interior to be rigid. Volcanoes are held by the majority to be of local, not deep-seated origin." *In 1936 a foundational paper described for the first time the existence of Earth's solid inner core surrounded by a liquid outer core.*

EAVESDROPPING ON THE ARCTIC

"There is no east, west or north at the top of the world, and therefore thousands of short-wave radio receivers on all sides of Earth will have an equal opportunity to tune in the messages broadcast by the aviator-explorers participating in the race to the North Pole this summer.

"The ethereal channels originating in the ice-capped region will be sprayed across the globe. Twelve Arctic expeditions are in preparation, and three are ready to hop off from northern points of land into the cradle of storms. Newspaper reporters, accompanied by radio operators and wireless equipment, have established a base at Point Barrow, Alaska, from where they hope to pick up radio signals and then relay the greatest news story of the year. It is expected that many amateurs operating short-wave sets will hear the narrative firsthand from the explorers within a fraction of a second after the words are released into the northern air because low wavelengths skip over short distances and travel far."



1876, The *Mygale* Spider: "This 'trapdoor' creature carries its eggs enclosed in a closely woven cocoon of white silk, forming two rounded pieces, united at their border."

DOOR-BUILDING SPIDERS

1876 "In the Paris Jardin de Plantes [a botanical garden in France], there is a curious spider belonging to the *Mygale* genus. Like all spiders, this strange creature has eight eyes. Its mandibles are armed with sharp teeth, and its feet have retractile claws, resembling those of a cat.

"The most curious member is indigenous to Corsica, a light brown spider that lies in tubes dug in clay banks. The tubes are vaulted from end to end with a hard mortar, and this in turn is lined with a soft, silky web. Before, however, covering his walls with their finest hangings, the spider fastens up a coarse fabric, and on this, as a foundation, the more delicate material is secured. Then he begins the construction of his door, in which operation it would seem that almost reasoning faculties are employed. Although scarcely one tenth of an inch thick, this door is constructed of upward of 30 alternate layers of web and mortar, each layer being imbedded in another, like a series of cups."

Scientific American, Vol. 34, No. 26; June 24, 1876

Soft botics

Carnegie Mellon University
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