

SCIENTIFIC AMERICAN



The Desperate Hunt
for Dark Matter

The Battle over
Elon Musk's Colossus
Data Center

Rewriting the History
of American Apples

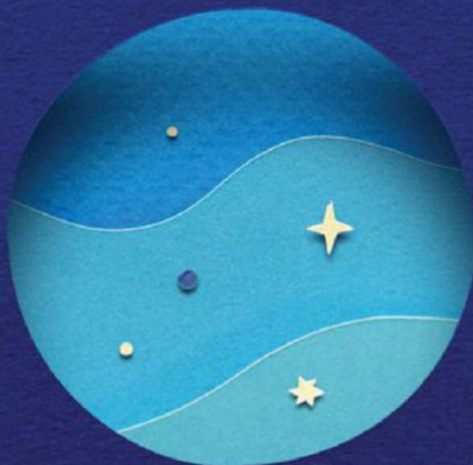
Impossible Questions

What came before
the big bang?

How did life begin?

What is consciousness?

Where science
hits a wall



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Some of the biggest questions in science—about the origins of space, life and consciousness—aren't just unanswered. They may be unanswerable. That doesn't stop scientists from trying.

Illustration by Owen Gildersleeve

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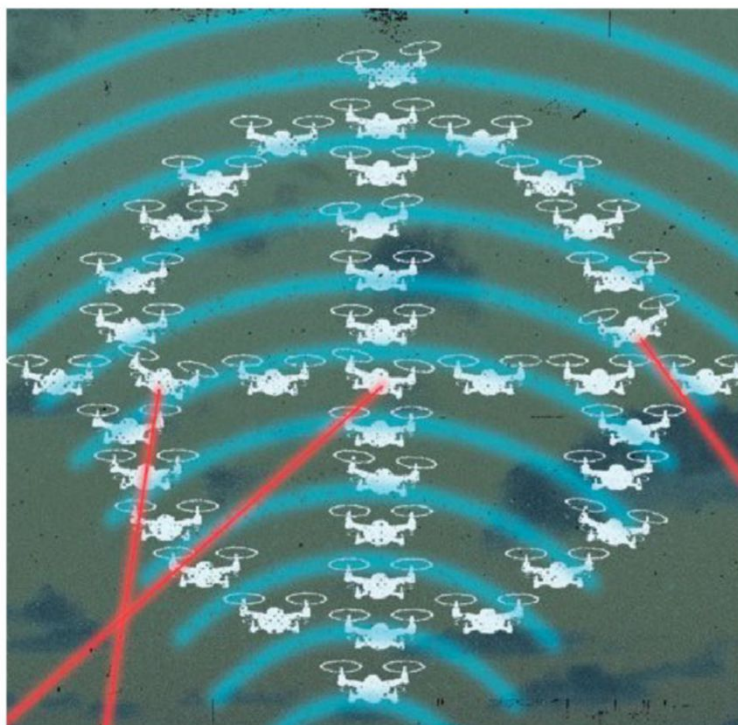
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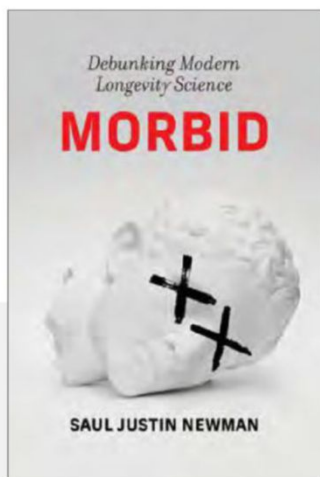
Google DeepMind

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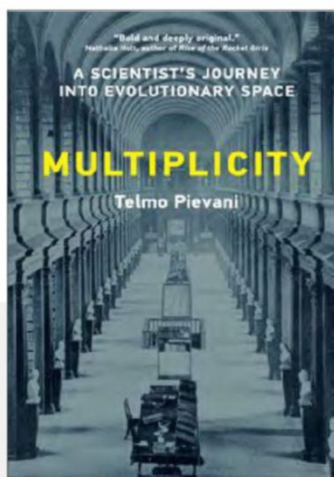
Morbid

Saul Justin Newman

A darkly comedic journey into the science of aging—where ethics are irrelevant, the studies are a sales pitch, and the “world’s oldest living people” all turn out to be dead.

“A brilliant skewering of aging secrets and lies.”

—*The Guardian*



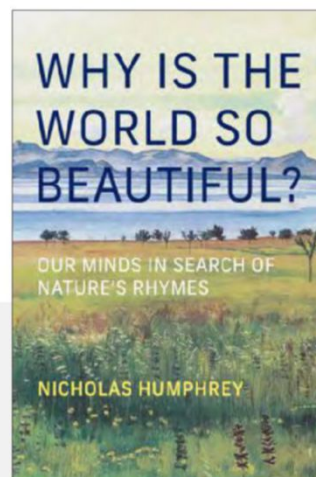
Multiplicity

Telmo Pievani

The awe-inspiring, little-known story of Nobel laureate Frances Arnold’s discovery of directed enzyme evolution—and how it was sparked by reading Jorge Luis Borges.

“This book is a jewel.”

—**David Quammen**, author of *Breathless*



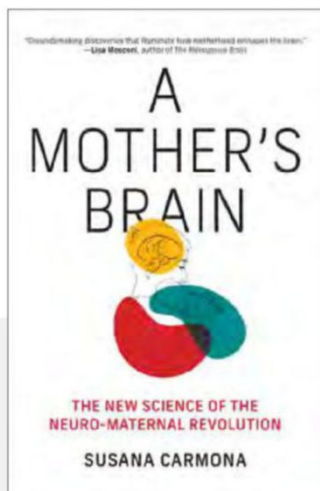
Why Is the World So Beautiful?

Nicholas Humphrey

A fascinating inquiry into why beauty matters and how it has played an evolutionary role in our understanding of the world.

“Humphrey’s skills as an expositor on the science/philosophy interface shine.”

—**Lord Martin Rees**, Emeritus Professor of Cosmology and Astrophysics, University of Cambridge



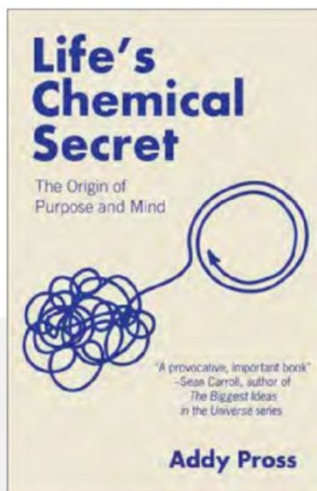
A Mother's Brain

Susana Carmona

An eye-opening account of how pregnancy transforms the brain even more profoundly than adolescence, drawing on decades of the author’s own pioneering research.

“A powerful, awe-inspiring, beautiful book.”

—**Lucy Jones**, author of *Matrescence: On Pregnancy, Childbirth, and Motherhood*



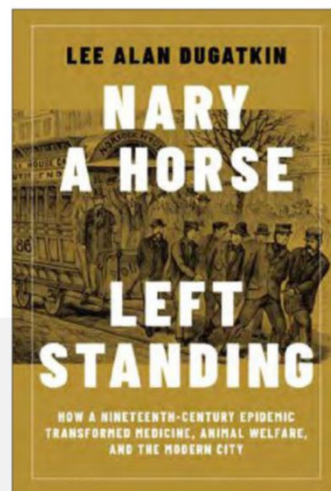
Life's Chemical Secret

Addy Pross

How the ground-breaking discovery of a new material form in chemistry—matter in a dynamic kinetic state—is helping to explain life’s unique characteristics.

“A provocative, important book.”

—**Sean Carroll**, Johns Hopkins University, author of *The Biggest Ideas in the Universe* series



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Lee Alan Dugatkin

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“A remarkable story of our never-ending battle with infectious disease and scientists’ determination to figure out the world around us. It’s a fascinating book—and one that matters.”

—**Deborah Blum**, Pulitzer Prize-winning author of *The Poisoner’s Handbook*

Finding Meaning in the Impossible

THERE ARE QUESTIONS in science that have been studied for so long without anyone turning up answers that they seem to move into the realm of “unsolvable” or even “impossible.” This is the realm we explore in *Scientific American’s* October issue (page 28).

When the editors first discussed this idea, a real concern became immediately apparent: Will our readers be disappointed at the very premise of an unanswerable question? Why dive in if we can’t satisfy their, and our, curiosity with a solution?

But we soon realized that this open-endedness is part of the appeal. Often the most fascinating questions are the ones with no obvious or direct rewards. Unlike figuring out the odds that someone will have a green-eyed baby, the knotty, impossible questions sit in uncharted territory. Scientists must approach them from many different angles, some of which require new tools and experiments never before conducted. Such undirected searching is exactly what fuels serendipity.

We probably wouldn’t have the blockbuster GLP-1 weight-loss drugs now reshaping medicine, for instance, if someone didn’t ask how Gila monsters cheat starvation—the lizards’ blood sugar never collapses even though they sometimes go months without eating. There was no obvious payoff to finding the answer and no pharmacology at the time that could explain the anomaly.

Alchemists searched for centuries for a way to turn common metals into precious ones such as gold—an impossible challenge when relying on a philosopher’s stone. Along the way, they established the field of chemistry and discovered the process of distillation that is ubiquitous today in water purification, pharmaceutical production and even fragrance making. (Physicists at the Large Hadron

Collider at CERN near Geneva accidentally did turn lead into gold recently, at least for a fraction of a second.)

For more than 2,000 years mathematicians chased a problem called squaring the circle, in which they tried to craft a square with the same area as a circle, using only a compass and a straightedge. Proof that it was impossible came with the discovery of transcendental numbers, which led to theorems that opened entirely new branches of mathematics.

On page 54 of the special report, philosopher Tim Bayne asks whether consciousness is real, a question that epitomizes the word “intractable”: the very act of studying it requires the faculty it’s trying to explain. But plenty of scientists have dedicated their lives to finding an answer. Along the way, that work has refined the tools we use to keep people safely unconscious under anesthesia. Other researchers turned to LSD and psilocybin to probe consciousness at its edges and found, serendipitously, that these substances carry real therapeutic effects for depression, post-traumatic stress disorder, and other resistant conditions.

The same pattern can be seen in the decades physicists have spent looking for the constituents of dark matter. The still unanswered question has led to ever more sensitive detector technology and a deeper understanding of what dark matter isn’t.

Although these “discoveries along the way” are meaningful, they might not even be the primary reason to pursue impossible questions. As physicist and *Scientific American* senior reporter Joseph Howlett writes of the search for dark matter (page 44), “Maybe the search for absolute truth—not just a reliably predictive picture of the world but a meaningful one—was always too ambitious.”

Perhaps the journey we take in our search for meaning is the goal. Humans are wired for curiosity and social connection. At the end of the day, impossible questions might satisfy both because they require us to ask why, how and what. All of science builds on the discoveries that came before and the people who made them. The intractable part could be the very thing that gives our lives meaning. ●

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On the Agenda



BioFuture Now: Pioneering the Future of
Biopharma Breakthroughs



AI & Deep Tech: Refining Health Innovation -
Drug Discovery, Diagnostics and Delivery



Health-as-a-Right Versus Health-as-a-
Business



From Seed to Scale: How will the Next Wave of
Biotech Get Financed



Next Wave of Innovation: Navigating Policy
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WORD FREQUENCY

"Discerning Chicks," by Cody Cottier [Advances], describes the so-called bouba-kiki effect, in which people around the world think "bouba" sounds round and "kiki" sounds spiky. The effect may be less about language than about simple spatial frequency perception for the visual system and acoustic frequency for hearing. Spiky images have more high-frequency information than rounded ones, and "kiki" has more high-frequency audio content than "bouba." Both visual and auditory systems have frequency-mapped neurons.

ROBERT I. MASTA ANN ARBOR, MICH.

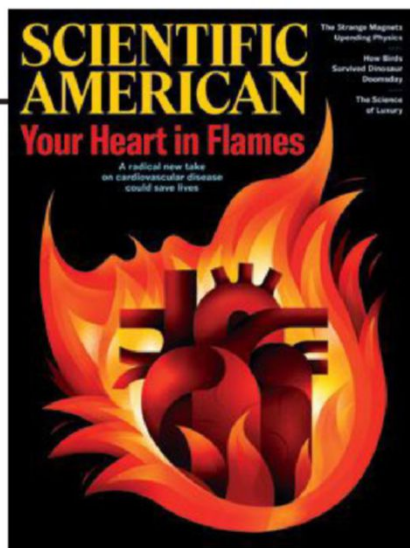
STARTING SPACE

"In Search of the Most Distant Galaxy," by Phil Plait [The Universe; April], got me thinking: if objects that are farther and farther away are older and older (as surmised from their redshift), then we must be getting closer to finding the beginning of the universe. I've always envisioned the big bang as a singularity that occurred at an actual point in space from which the universe then expanded. If so, wouldn't the oldest objects in the sky all converge to a single location, thus showing us the center of the universe, or at least where the big bang originated?

RALPH LUNN

CASTLEGAR, BRITISH COLUMBIA

PLAIT REPLIES: *This is a common question, but it relies on a misconception that's hard to break: People often think of the big bang as an explosion in space. Yet it was actually an expansion of space. At that time, the entire cosmos, including space itself, burst into being. That means the big bang happened everywhere. That's a difficult concept to grasp, even for cosmologists. But it means the universe can expand without expanding into anything and didn't have an origin point in space. So we see distant galaxies in every direction we look in the sky, not just in one direction, and that same observation is true for every galaxy in the universe. The big bang was everywhere, so there's no one*



May 2026

place you can point to and say, "It happened thataway." It happened allaway.

FUELING UNCERTAINTY

"War's New Fuel," by Sarah Scoles [The Science of War; April], suggests a new way to recover valuable elements from spent nuclear reactor fuel. The article left me wanting. Fuel reprocessing is a highly complex and nuanced field that raises myriad issues involving contamination, proliferation hazards, material flows and ultimate disposal. The article makes it seem like someone flourishes a wand and all this goes away, leaving only plutonium "chemically trapped in a messy soup." But what happens to that soup as a waste stream, and could the plutonium be extracted from it later?

DAVID BERWALD TEANECK, N.J.

ORCHESTRAL RUN

In "Lost in the Music" [Advances; April], Jesse Greenspan describes how music with a strong, rapid beat generates vigorous up-and-down movements, whereas more gentle music causes sideways swaying movements. This brings to mind my experiences a few decades ago when I skied while

listening to music with one of the rather primitive wearable cassette-tape players that had just hit the market.

I would ski a steep slope at a wild maximum to the energy of the orchestral piece "Sabre Dance," flying from one mogul to the next, and I discovered that the music seemed to have the effect of detaching my conscious thoughts somewhat, relaxing my tension, so my body could work from "muscle memory." This both smoothed my style and improved my accuracy in landing each time on the next mogul.

DAVID WILLIAM BROWN

VICTORIA, BRITISH COLUMBIA

FLUSH WITH ENVY

I have to disagree with one point in Cody Cottier's story "Making Faces" [Advances; April]. In describing how we make tailored, as opposed to automatic, facial expressions, he gives the example that "we've all... tried not to smile while holding a royal flush." I doubt we've all had that experience: either Cottier has an incredible amount of good luck, or he plays much more poker than I do.

BRAD DIBBLE MIDHURST, ONTARIO

POLITICAL SCIENCE

Inspired by "State of American Science," by Adam Rogers [Young American Scientists; July/August], our online Discussions space asked readers, "What role do you think government should play in science?" The following responses were edited for space and clarity.

The U.S. government should return fully in its support for scientific research. Since World War II the U.S. government has supported scientific research through a thorough grant process, and it must return to its previ-

"The U.S. government should return fully in its support for scientific research."

—ROBERT MONTEMURNO VIA DISCUSSIONS

ous partnership with research institutions, both private and public. It is vital for the U.S. to lead the world in research to advance technology and for the betterment of the health of humankind.

ROBERT MONTEMURNO

VIA DISCUSSIONS

Your question is too short-term and ignores the underlying cause of our predicament. The lay public is the ultimate arbiter of government policy. During the past 30 years, it has steadily decreased its trust of academic scientists because they have become so politicized that they have been viewed more as preachers than as honest brokers of data. The phrase “settled science” is a key symptom of the preaching arrogance. To members of the working class, university elitists are more interested in ideologies than their everyday struggles to live even a shred of the American dream. “PROF. H. WINET” VIA DISCUSSIONS

BEING GREEN

In “[Something in the Water](#)” [April], Cody Cottier discusses mountain lakes that are turning green because of algal blooms. Norway also has green lakes but for a different reason: fine-grained sediment from glacial deposits creates a deep-green look when seen from above. Consider the well-known [Lake Gjende](#). Nearby [Lake Bessvatnet](#), which does not receive such deposits, is deep blue. ERIK MØNNESS RENA, NORWAY

ERRATA

In “[Aurora Poetry](#),” by Jacek Krywko [Advances; July/August], the caption for the image of a hand-copied version of the diary *Meigetsuki* should have specified that the copy dated to the Edo period. The diary was originally written in the Heian and Kamakura periods.

“Spying on the Universe,” by Jonathan O’Callaghan [September], should have said that results published in 2024 by astronomers working with the Dark Energy Spectroscopic Instrument suggest that dark energy might be weakening.

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Letters may be edited for length and clarity. We regret that we cannot answer each one.

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ADVANCES

ECOLOGY

Living Fog

Scientists are lifting the fog on a hidden microbiome

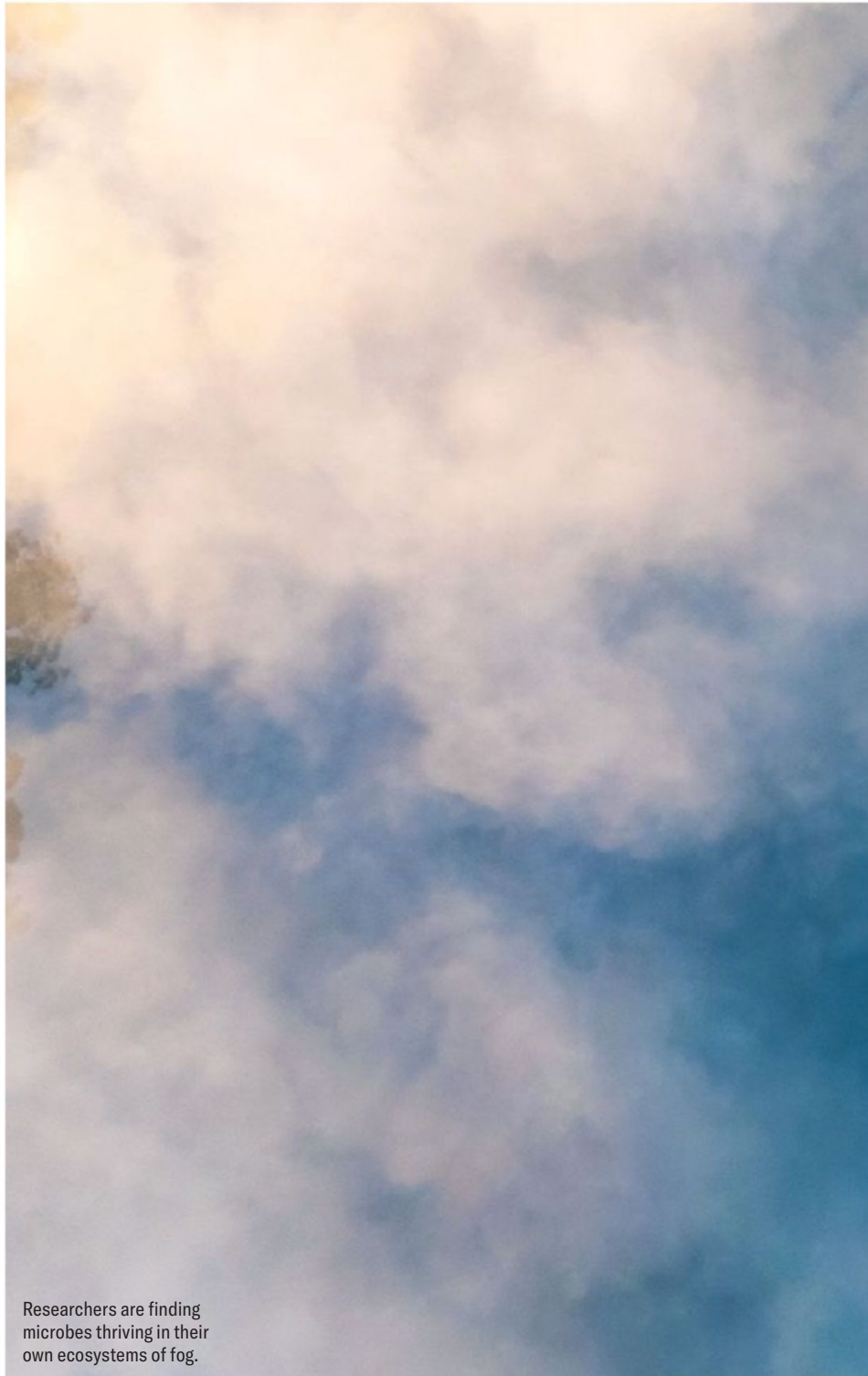
FOG HAS AN EERIE and enchanting way of coloring how humans perceive our surroundings—and scientists are discovering that the atmospheric phenomenon may remake microbes' experience of their environment, too.

Ecologists have primarily considered fog a source of desperately needed moisture for desert inhabitants as well as a vector for moving nutrients and microscopic organisms around. Until recently, very few have considered fog itself as a potential habitat or even ecosystem.

"The scientific community has known for a long time that there's a lot of microbes in the atmosphere," says Ferran Garcia-Pichel, a microbiologist at Arizona State University. "But is it just a vehicle for transport, or are the microbes really active and doing stuff in the air? That's a fundamentally different question because then the atmosphere becomes a habitat."

Garcia-Pichel is a co-author of research published in *Environmental Microbiology* that investigated microbial activity in fog water collected from a site in Pennsylvania. The researchers discovered bacteria feasting on simple carbon compounds within the liquid and found larger numbers of bacteria after fog events than before them—suggesting that the organisms are actually growing. "Perhaps slow growth, but growth is also slow in the Arctic because of temperature, and nobody questions that's a habitat."

Garcia-Pichel and his colleagues



Justin Paget/Getty Images

Researchers are finding microbes thriving in their own ecosystems of fog.

BACTERIA SEND PROTEIN
PACKAGES TO HELP
ONE ANOTHER SURVIVE P. 10

WE NOW KNOW HOW
AVOCADO TREES
SWITCH SEXES DAILY P. 15

A PREFERRED SIGNALING
TEMPO REPEATS
ACROSS NATURE P. 18

DISPATCHES FROM THE FRONTIERS OF SCIENCE, TECHNOLOGY AND MEDICINE



are particularly intrigued by the specific bacteria they found in the fog—known species often found on plants and in soil. “They’re really colorful—they’re pink or red,” he says; the pigments also protect against light, so they may serve as a defensive measure against harsh radiation in the atmosphere. The bacteria also happen to metabolize formaldehyde, a rare capability that researchers can spot signs of in fog water. (Processing compounds like formaldehyde with only one carbon atom is a trickier task than consuming common carbon-rich sugars—one that requires special cellular machinery.)

The finding is a key development

for the burgeoning field of fog microbiology, says Eli Dueker, an environmental microbiologist at Bard College, who was not involved in the research.

“This [study] really takes it to that next level and demonstrates, yes, they are metabolizing at least formaldehyde, and they are changing the chemistry of the atmosphere,” he says. “It might be more ephemeral or temporary than an island, say, but fog droplets are creating tiny microhabitats.”

Fog forms and dissipates and moves, all without a care for scientists’ experiments, and bacteria are difficult to keep tabs on. “You can’t mark microbes in the same way you might put a collar on a bird,” says Sarah Evans,

a microbial ecologist at Michigan State University, who with Dueker published earlier work [tracing oceanic microbes in fog over coastal Namibia and Maine](#).

Still, scientists are working hard to put fog under the microscope. Take, for example, research published earlier this year in *Communications Earth & Environment* that [identified microbes living in fog in the Amazon rainforest](#). That study was based at a facility called the Amazon Tall Tower Observatory, an outpost about the height of the Eiffel Tower. The view is incredible, of course. “It’s beautiful; it’s a green ocean,” says Ricardo Godoi, a chemist at the Federal University of

MICROBIOLOGY

Collective Survival

Bacteria send one another protein packages to withstand antibiotics

WHEN ANTIBIOTICS ATTACK MICROBES, their stressed neighbors ship them proteins that help them survive, new work suggests.

Bacteria share DNA related to [antibiotic resistance](#) through a process called [horizontal gene transfer](#), but microbiologists have long suspected they might trade more than just the genes. Multiple research papers have proposed that microbes use vesicles, tiny fluid-filled bubbles enclosed in fatty membranes, to ferry working proteins to their buddies as well. “But if you go back to these papers, there was no evidence,” says Christophe Herman, a microbiologist at the Baylor College of Medicine. In a recent study [published in the journal *Science*](#), Herman and his colleagues have, for the first time, caught bacteria in the act of transferring functional proteins to one another in this way.

To achieve this, the scientists created two *Escherichia coli* bacterial populations. One group of cells, the recipient bacteria, carried a disabled, inverted gene that made them unable to metabolize a simple sugar called galactose. A donor bacteria population, in turn, had the ability to create a protein named Cre recombinase that could fix the inverted gene in the recipients. With a working version of that gene, the recipient bacteria, in theory, could again feast on galactose. Only a cell that physically received the Cre protein could flip that gene back on.

“[Herman] went on vacation, and I was in the lab doing these experiments. I don’t think we thought anything would come of it,” recalls study lead author Alice X. Wen, a microbiologist also at Baylor. But to the research-

Continued on page 12



Ted Horowitz Photography/Getty Images

Paraná in Brazil and co-author of the research. “You just see a green carpet. It’s marvelous.”

For that study, researchers climbed up the observatory to the very top of the surrounding forest to snag samples of the early-morning fog, managing to catch water from a precious 13 different fog events. Inside those samples, scientists identified more than a dozen different species of both fungi and bacteria. Many of them are known from more traditional ecosystems to be important players in nutrient cycling and breakdown of dead material, although the research couldn’t confirm whether they were filling these roles in the fog.

It’s perhaps been anthropocentric not to consider fog as a cozy habitat for microbes. “Living in a fog droplet could be a pretty good life,” Evans says. “You’re protected from the sun; you have moisture, other nutrients maybe.”

So far the studies identifying microbes in fog remain as elusive as fog itself—but scientists say that reflects only the limits of research to date, not of life. “I’m just so delighted to see more research,” says Kathleen Weathers, an ecosystem scientist at the Cary Institute of Ecosystem Studies in Millbrook, N.Y., who describes herself as the “senior stateswoman” of fog research. “I think this is just the beginning.”

—Meghan Bartels

Escherichia coli in a petri dish



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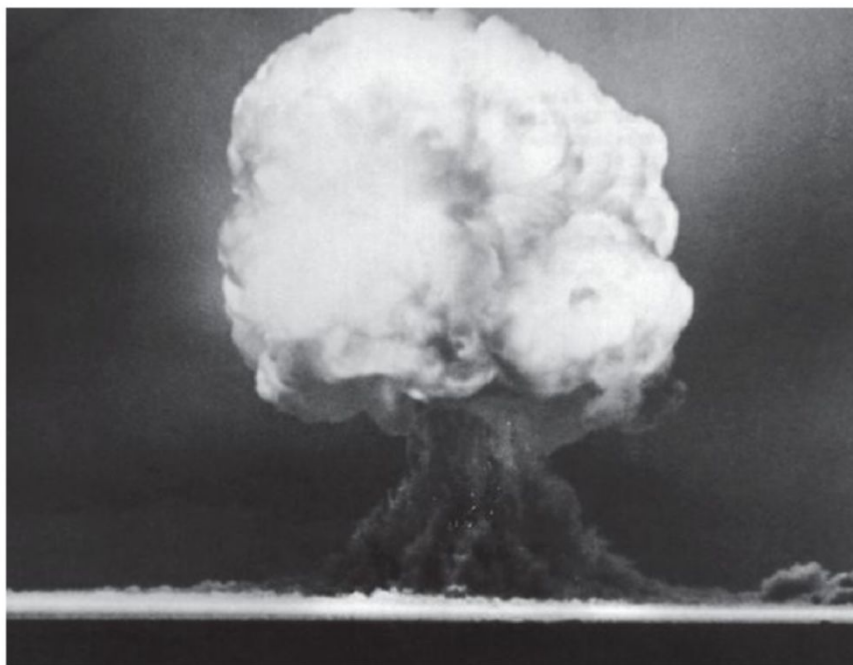
ers' surprise, the bacteria in fact sent proteins to one another, albeit very slowly. The team then found that exposure to certain antibiotics kicked the exchange into high gear, making the protein-transfer rate jump roughly 4,000-fold.

In nature, antibiotic stress splits bacteria into two camps. Most cells ramp up a membrane stress response and shed vesicles loaded with protein cargo, leaving themselves exposed to the antibiotics. The others go dormant, shutting down protein production and reproduction to survive the antibiotic onslaught. Herman suspects incoming vesicles deliver repair proteins that the dormant cells can no longer make themselves, such as a DNA polymerase to restart replication when the bombardment is over. In the lab, this exchange even occurred when the donor and recipient cells were different bacterial species.

The researchers don't yet know why stressed cells help their neighbors survive. "We just know at this point that it happens," Wen says. Herman speculates that, besides working as a population survival mechanism, capturing a neighbor's protein could also let a cell sample what it has to offer—going through a microbial version of a free trial before committing to something more permanent, such as taking its DNA.

This study, which had multiple control groups to rule out other explanations for the bacteria's survival, "is a very elegant way to demonstrate that there actually is protein transfer," says Laurence Van Melder, a microbiologist at the Free University of Brussels, who was not involved in the study but co-authored an accompanying commentary in *Science*. "I'm pretty confident they have the right thing," she adds.

Scientists hope this mechanism's discovery will one day help us stop bacteria from mutating to withstand antibiotics. "Persistence is the first step to resistance," Herman says. "If we could stop that, I think it would be very helpful in stopping the rise of antibiotic resistance." —*Jacek Krywko*



The fireball from the Trinity nuclear test in New Mexico on July 16, 1945

CHEMISTRY

Bomb Substance

Strange crystals have been found inside wreckage from the first nuclear bomb test

ALMOST EXACTLY 81 YEARS AGO the first nuclear bomb exploded. In the Trinity test, conducted in the New Mexico desert, a Manhattan Project team detonated a plutonium bomb that released the energy of 25 kilotons of TNT. When the mushroom cloud faded, melted sand combined with vaporized sensor wires to create a weird, glasslike form of matter. Scientists called it trinitite.

Now researchers have identified a new material within trinitite called a clathrate: a cagelike chemical lattice that traps other atoms inside it. "It's a completely new kind of clathrate crystal—something never seen before in nature or in the products of a nuclear explosion," says Luca Bindi, a geologist at the University of Florence in Italy, who is a co-author of a study detailing the finding in the *Proceedings of the*

National Academy of Sciences USA.

The strange material is the result of very unusual conditions. During the Trinity blast, sand swept into the ensuing fireball was exposed to temperatures higher than 1,500 degrees Celsius and pressures of several gigapascals—tens of thousands of times the normal atmospheric pressure and enough to



A new clathrate was found in this trinitite sample from the Manhattan Project's bomb blast.

Underwood Archives/Contributor/Getty Images; Luca Bindi, Marek Mihalović, Michael Widom, Paul J. Steinhardt/PNAS

squeeze graphite into diamond. Matter vaporized, mixed and cooled extremely quickly, scrambling into new forms. “This all happened in a matter of seconds, so atoms didn’t have time to arrange into stable structures, leading to unusual nonequilibrium materials like this one,” Bindi says.

The clathrate was found inside a copper-rich metallic droplet embedded in the trinitite. The clathrate’s “cage” shapes are 12-sided dodecahedrons and 14-sided tetrakaidecahedrons made of silicon atoms, with calcium atoms—and sometimes copper and iron atoms—trapped inside.

“The transient extreme conditions of the Trinity test allowed for the formation of metastable phases that might not be found in laboratory experiments,” says G. Nelson Eby, a geoscientist at the University of Massachusetts Lowell, who has previously collaborated with some of the study authors but was not involved in this research. “This is an interesting new addition to the clathrate universe.”

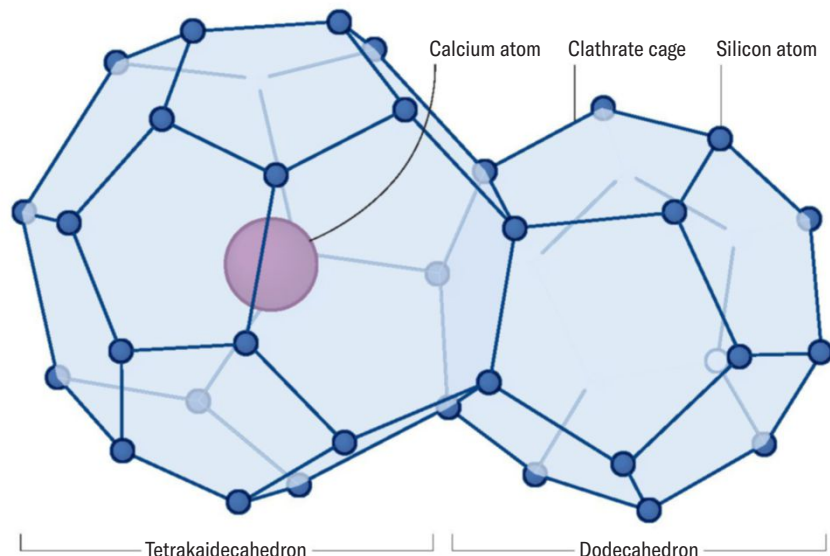
The clathrate variety isn’t the only novel chemistry that has been discovered within trinitite. In 2021 researchers found a quasicrystal—a kind of matter scientists once thought impossible that challenges traditional ideas about how solids form. Quasicrystals

have an ordered structure, but their atoms don’t repeat periodically like those in typical crystals. The only other known naturally forming quasicrystal material was found inside meteorite fragments, and scientists think it was created during the fiery collision of two asteroids when the solar system was young.

The quasicrystal seen in trinitite is made of the same four elements—iron, silicon, copper and calcium—that make up the newfound clathrate. And the quasicrystal “is especially intriguing because it formed under the same extreme conditions and still hasn’t been reproduced in the lab, making it a rare example of a structure that nature created but we cannot yet fully replicate,” Bindi says.

The scientists theorize that the two types of crystal formed under the same temperatures and pressures in the blast, but the quasicrystal formed in areas where copper was readily available, whereas clathrate emerged where copper was scarce.

“This work underscores how rare, high-energy events—such as nuclear detonations, lightning strikes, and hypervelocity impacts—serve as natural laboratories for producing unexpected crystalline matter,” the study authors write. —Clara Moskowitz



Source: “Extreme Nonequilibrium Synthesis of a Ca–Cu–Si Clathrate during the Trinity Nuclear Test,” by Luca Bindi et al., in *Proceedings of the National Academy of Sciences USA*, Vol. 123, No. 21, May 11, 2026 (reference)

Graphic by Amanda Montañez

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Fundamentals First Fund

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2/21/24 IPO Market Open: \$10.00
8/18/26 Market Close: \$13.12
Dividends Paid: \$ 0.41

Abstract

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ROBOTICS

Cubes with IQ

Smart bricks display collective intelligence like biological bodies

CELLS DO NOT HAVE BRAINS. Yet somehow, as an organism grows, cells know where to go and what to be without top-down direction. And acting together, cells are collectively intelligent, ultimately building complex final forms—whether that be a flower, a whale, or even you. Mimicking this ability in machines could one day lead to self-healing circuits and computers that can assess and repair damage as it happens, and new research published in *Nature Communications* shows how smart “bricks” could move us closer to that goal.

A future in which machines build themselves is “all about local self-organization where you don’t have one failure point,” says Sebastian Risi, the paper’s senior author and a computer scientist at IT University of Copenhagen and Sakana AI.

First, the researchers created simulations of cubes, each with an independently operated neural network, assembled into nearly 500 3D shapes across seven object categories—boats, cars, chairs, guitars, houses, planes and tables—and tested whether the cubes could identify their category. Each virtual cube contained a list of numbers called a vector with its memory and a guess about object category, both of which can evolve over time. Each cube’s neural network told it how to update its vector

based on its neighbors’. Together, the cubes formed what’s called a neural cellular automaton. (The classic example of cellular automata is [John Conway](#)’s Game of Life, devised in 1970, in which pixels flash on and off based on how many neighbors they have.)

The simulated cubes passed messages and altered their vectors based on, first, their own immediate environment, such as whether they were on an edge, then their neighbors’, and so on. After the neural network was trained, cubes named their object class with 85 to 100 percent accuracy—houses proved trickiest. “It’s remarkable that the bricks can infer the global shape of the collective using only local information,” says Sabine Hauert, who studies swarm robotics at the University of Bristol and was not involved in the work.

The virtual cubes could often identify their shape even if 15 percent of them had been removed, as well as decide which cubes were missing and regenerate neighbors. And the team found that systems of more than 18,000 cubes could still guess the objects they were in.

Finally, the researchers tested their system using real blocks, each a few centimeters across, with circuitry inside that ran computations locally. When up to 197 were connected into a shape, they accurately identified what object they were 100 percent of the time.

Risi says a near-term application is in edutainment: build a dinosaur that then roars, or use construction bricks that tell you where to place the next one. Over the long term, the researchers envision modular robots that assemble themselves, no instruction manual required.

—Matthew Hutson

GENETICS

Flexible Flowers

Avocado trees switch sex daily, and now we know how



Avocado flowers in their female phase

A REMARKABLE DANCE OCCURS between the flowers of avocado trees every spring: the trees change sex daily, moving from female to male or male to female, then back before the next morning. Botanist A. B. Stout observed this reproductive strategy as early as 1927, but researchers couldn't explain how it worked until now.

All avocado trees (*Persea americana*) are cosexual, or hermaphrodites, meaning they contain both sexes in one plant. A-type trees begin with flowers in the female phase (receptive to pollen) in the morning and change to the male phase (producing pollen) in the afternoon of the next day. B-type trees operate on different timing, making them male in the morning and female in the afternoon. For a new study in the *Proceedings of the National Academy of Sciences USA*, Jeffrey S. Groh, a postdoctoral researcher at the University of California, Berkeley, and his colleagues pinpointed a single protein-coding gene that lets A- and B-type trees inherit the sex-swapping behavior. The protein it produces activates a host of additional genes to coordinate flowers opening and closing in rhythm to aid the trees' reproductive strategy, letting "the whole tree [pulse]

female to male or male to female," he says.

Cathy Rushworth, a plant evolutionary geneticist at Utah State University, who was not involved in the study, says the gene region in question shows a very clear signal in this work—almost like it can "glow in the dark." Tools to reveal this level of detailed genetic information, she adds, have only recently become available and inexpensive enough to see wider use.

Flowering plants, called angiosperms, employ an immense diversity of reproductive strategies. And although the strategy used by avocados is found in a few other species in the same family, the researchers determined that it was not driven by the same mechanism in, for instance, the distantly related true cinnamon. This, they say, indicates that it most likely evolved separately multiple times. The genetic evidence suggests avocados' ancestors picked the habit up about 40 million years ago.

"Through the power of genetics," Groh says, "we can detect traces of this rhythm far into the ancient past, a humbling reminder that our own experience of this beautiful phenomenon is just a tiny sliver of its evolutionary history."

—Jeanne Timmons

ASTROPHYSICS

Strange Duos

Mismatched black hole pairs form across the cosmos

WHEN TWO BLACK HOLES FIND each other in the vastness of space, they can form a binary odd couple—and it's more common than researchers expected.

Scientists think most black holes are born when a star dies and its core collapses. This is also the case for binary black holes, pairs of black holes that orbit around each other and slowly move closer together. These pairs are often the remains of stars that lived together, died together and continued to coexist following their collapse. Eventually these two draw close enough together to merge into one faster-spinning black hole that sometimes shoots off into space.

Now research is suggesting that these whirling loners can find love again. New work suggests many black hole pairs are so-called hierarchical mergers: one large, fast-spinning black hole born from a previous merger and the partner it somehow found in the cosmos. This picture of black holes' origin stories could help clarify how supernova physics work and how galaxies evolve, scientists say. Knowing how black holes form and change is also crucial for understanding general relativity and the history of the universe.

In two studies released recently in *Physical Review Letters*, scientists describe how they used published data from the Laser Interferometer Gravitational-Wave Observatory, which tracks merging black holes through the spacetime ripples they release, and other observatories to identify this subpopulation. Each team used a different technique to track the black holes' mass, spin and tilt, and both captured a distinct group of binary

black holes that have “strong signatures” of hierarchical merging—one of the pair is much larger, is spinning faster and orbits out of alignment with its partner.

“At minimum, we’re finding evidence that there are these highly spinning and weirdly tilted black holes in the dataset, and the most straightforward way to interpret that, the Occam’s razor answer, is that these black holes probably came from previous mergers,” says Cailin Plunkett, lead author on [one of the recent studies](#) and a Ph.D. candidate at the Massachusetts Institute of Technology. Her study suggests about 14 percent of black hole duos may be hierarchical mergers.

Physicists had previously predicted that the offspring of black hole mergers in dense stellar environments would find future partners to merge with. And their different astrophysical history

would make them operate “in weird and wonderful ways”—a sign that researchers have now spotted, says Paul Lasky, co-author of [the other recent study](#) and an astrophysicist at Monash University in Melbourne, Australia.

The fact that two different technical processes both found evidence of these black hole origins is “a concrete example of us moving astrophysics forward,” says Maximiliano Isi, an astrophysicist at Columbia University, who was not involved in either study but has worked with LIGO data in the past. “It’s kind of like trying to see on the road when there’s fog,” Isi says. “We’re all squinting in different ways and looking from different angles and trying to determine what is the landscape of what’s out there, and we are converging into a very nice picture that somewhat aligns with theoretical expectations.”

—Mary Randolph

MATH

Haphazard Hanging

Mathematicians discover the worst way to hang a painting

YOU HAVE TWO NAILS in the wall and a painting with a string on its back, which can easily be rested on the nails to hang the painting. If you remove one nail, the painting will still hang on the other. But mathematicians said, “We can make it worse.” In 1997 A. Spivak posed the following riddle: Is there a way to hang the painting so that removing either nail will cause the painting to fall? Since then, mathematicians have expanded this concept into an intriguing family of picture-hanging problems.

Retired computer scientist Tom Verhoeff first explored such problems in a workshop for a grade school math camp, where the campers investigated with [actual string](#) and carabiners but also translated the problem into symbols ([graphic on opposite page](#)).

In 2012 mathematicians posted a preprint proving that solutions exist for any k -out-of- n picture-hanging problem, where n is the number of nails and removing any k of the nails, but no fewer, will cause the painting to fall. Known solutions, however, can involve very elaborate string wrappings. At the workshop Verhoeff and the participants tackled the 2-out-of-4 problem, in which a painting will fall if any two of four nails are removed. They reduced the length of the shortest known solution from 80 to 58 wraps around the nails.

Later, Verhoeff worked it all the way down to 18—and, with the help of then Ph.D. student Jens Heuseveldt and a computer program to check all smaller hangings, down to the absolute minimum of 16. Initially Verhoeff showed

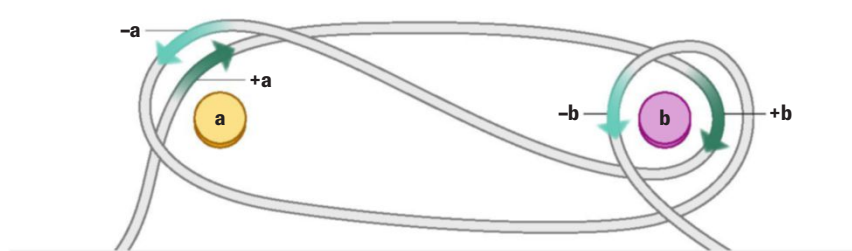


Heuseveldt a computer program to solve the problem in about two hours. “I then told him my program could solve it in two seconds,” Heuseveldt says. “And now his program is even faster than mine.” Verhoeff posted the results along with the shortest known explicit solutions for large families of these problems to the preprint server [arXiv.org](https://arxiv.org).

Why are mathematicians so interested in hanging paintings in complex and terrible ways? Although the problem’s framing might sound silly, the underlying mechanics have deep connections to group theory, knot theory, graph theory, and other areas of mathematics. In the 1-out-of- n case, for example, solutions can be described as loops drawn on the edges of an n -dimensional cube that pass through every corner. Plus, it’s possible to find hangings for any “reasonable” set of rules for paintings to

One Solution to the 1-out-of-2 Picture-Hanging Problem

Here the string wraps around the first nail clockwise, then the second nail clockwise, then the first nail counterclockwise and finally the second nail counterclockwise. By calling the nails **a** and **b**, this solution can also be represented as $+a + b - a - b$, a solution of length 4. If we remove nail **a**, we are left with $+b - b$, which cancels out, and the painting will fall. The same is true for removing nail **b**.



fall—for example, you can’t require that removing just nail A makes the painting fall but removing A and B leaves it hanging. These rules exactly correspond to the monotone Boolean functions—a function type crucial in fields such as cryptography and voting theory.

But asking whether the problem is useful is the wrong question, Verhoeff argues. “For humanity as a whole, we don’t know where our spaceship is going and what we will need to survive,” he says, “and play is one of the ways in which we learn.” —Emma R. Hasson

MATH PUZZLE

A Puzzling Picture

By Emma R. Hasson

HANG A PICTURE on three nails so that removing any two will cause the picture to fall but removing just one will not.

HINT: See the solution for two nails in the neighboring article: clockwise around a, clockwise around b, counterclockwise around a, counterclockwise around b, also notated $+a + b - a - b$.

CHALLENGE: Hang the picture on three nails so that removing any one nail will cause the picture to fall.

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

ZOOLOGY

Demon Cave Fish

This eyeless oddball hid in an Alabama military installation for 40 years

SOME HILLS in northern Alabama are burial mounds from the Copena people who lived there 2,000 years ago. Some contain decommissioned nerve gas from the cold war. But one holds a portal to the underworld—a low-slung knoll in a restricted military installation leads to a cramped but sprawling limestone network called Bobcat Cave, where scientists have discovered a strange, eyeless creature they’ve dubbed the demon cave fish.

The cave isn’t exactly welcoming to human visitors. “You’re stooped to hands and knees, crawling, and depending on the water level, you could be in neck-deep,” says Matthew L. Niemiller, a cave biologist at the University of Alabama in Huntsville. But because the system is a stronghold for the endangered Alabama cave shrimp, monitoring teams have explored the cave nearly every month since the early 1990s.

Despite this scrutiny, the demon cave fish was discovered only recently and completely by chance. On a routine survey in February 2025, Niemiller slipped in the red Alabama mud and fell headlong into a deep pool of water—and found himself face-to-face with a creature he didn’t recognize. This fish had a humped back and a slightly duckbilled snout, and, unlike the slightly more colorful Southern cave fish already known to inhabit the system, it was so ghostly white it looked blue under their headlamps. “It’s a shock and kind of embarrassing, in a way,” that it escaped notice for so long, says Niemiller, lead author of a paper presenting the new species and genus in *Scientific Reports*.

Genetic analyses suggest the demon cave fish and the Southern cave fish aren't closely related and made their way underground separately: it appears they lost their vision because of different mutations. The study authors say it's surprising to see two cave fish species living in not just the same cave system but the same pools and chambers. Whereas other cohabitating cave fish are like neighbors, the demon and Southern cave fish are like roommates—if those roommates had been trapped together for millions of years and potentially snacked on each other's children.

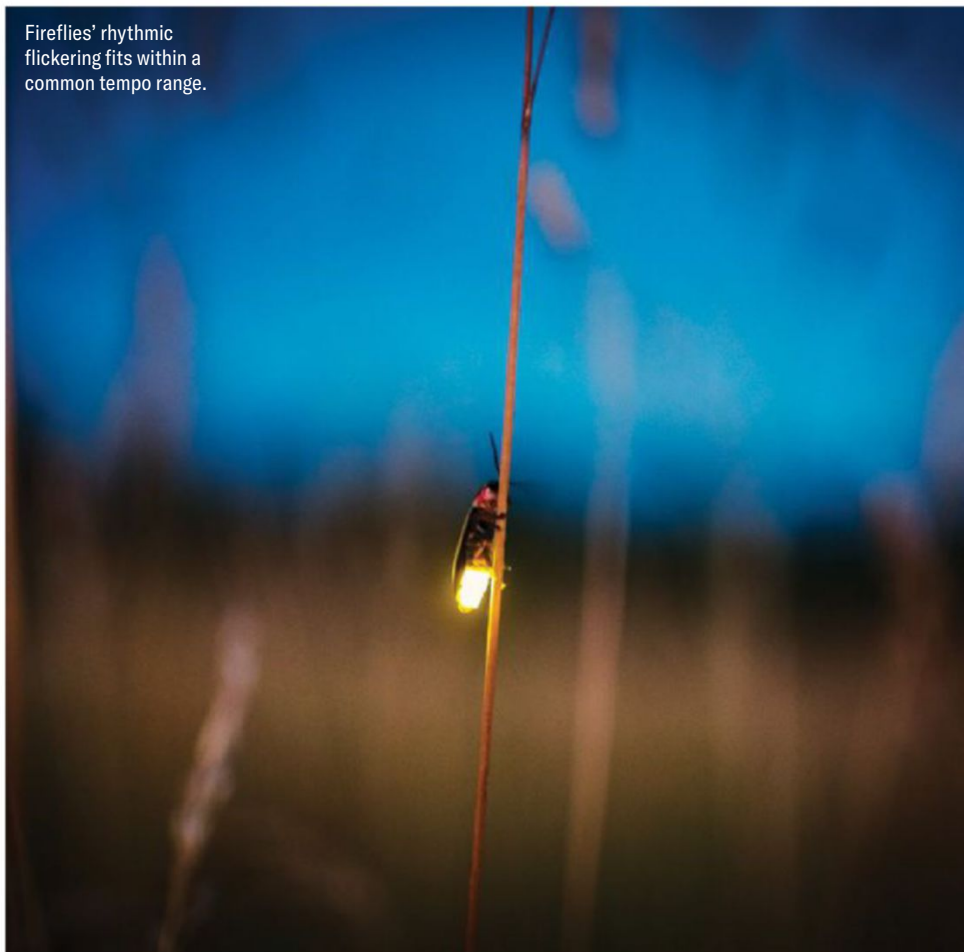
Niemiller and his team have named the new species *Demogorgonichthys arcaneus*, a wink to the otherworldly creature that emerged in a secret federal lab in the Netflix series *Stranger Things*. The finding is a humbling reminder of how much biodiversity remains undocumented even in the best-explored caves, says Suzanne McGaugh, an ecologist and cave fish expert at the University of Minnesota, who wasn't involved in the new study. "We owe a debt of gratitude to them for their discovery," she says.

—Elizabeth Anne Brown



The newfound demon cave fish

Fireflies' rhythmic flickering fits within a common tempo range.



NEUROSCIENCE

Rhythm of Life

Nature may have a preferred tempo

WHILE IN THAILAND'S MANGROVE forests filming *Pteropteryx malacca* fireflies, known for synchronized flashing, researchers noticed a coincidence: nearby crickets appeared to chirp in time with the flashing insects. "I thought, whoa, could the two be interacting?" says Northwestern University biophysicist Guy Amichay, lead author of a new study on the phenomenon. "It also blew my mind because it's light versus sound."

A closer analysis showed that both produced signals at nearly the same tempo—about 2.4 hertz, or roughly 145 beats per minute.

While the tempos' extreme closeness may indeed be coincidental, a survey of animal communication studies revealed that a broader range—around 0.5 to 4 hertz, or 30 to 240 beats per minute—appeared repeatedly across animals varying enormously in size, from fireflies and fiddler crabs to fish, birds, apes and humans.

The researchers, who reported their findings in *PLOS Biology*, also screened 124 recordings from the vast wildlife sound archive *xeno-canto* and identified 50 species with regular rhythmic signals. These, too, clustered within the

Matthew L. Niemiller/UAH (demon cave fish);
Jeremy Hogan/Getty Images (firefly)

same tempo range, with a peak around 180 beats per minute.

“That there might be a common rhythm across a remarkably diverse set of species and communication systems is very intriguing indeed,” says University of Amsterdam music cognition researcher Henkjan Honing, who was not involved in the study. Most popular Western music fits within this range at around 120 beats per minute (2 hertz), he adds.

Many of these species are physically capable of signaling at tempos outside this range, too. So why don’t they? To answer that question, the researchers shifted their attention from signal senders to receivers—because all signals are ultimately processed by nervous systems that are made up of neurons.

Neurons don’t respond instantaneously to incoming signals; their responses can depend on input received over the previous few hundred milliseconds. The researchers wondered whether this processing time might make neural circuits especially responsive to certain tempos, much as the time a swing takes to move back and forth on a swing set determines when a push will have the greatest effect. A computer model suggested simple neural circuits built with an internal “tempo” of 120 beats per minute responded best to signals that were also around that range.

The findings echo decades of research on human rhythm perception, says Cornell University cognitive scientist Nori Jacoby, who was not involved in the study: although humans can synchronize across a wide range of rhythms, beat perception and production tend to peak within a preferred tempo range of roughly 85 to 120 beats per minute.

Honing cautions that the neural explanation is only one possibility. Other biological rhythms, such as movement or breathing, could also help set the pace of animal communication—leaving open how vastly different species arrive at similar tempos.

—Anirban Mukhopadhyay

ANIMAL BEHAVIOR

Flying Enjoyers

Does flying spark joy? Scientists asked cockatoos



Galah Cockatoos

AS A KID, Jorg Massen would watch birds swoop and swirl overhead and wonder whether they were doing it for enjoyment. Massen is now a behavioral biologist at Utrecht University in the Netherlands, and thanks to a special setup at a nearby bird park, he was finally able to put that question to the test.

For several months each year the birds at Avifauna Bird Park are free to leave their aviaries at certain times every day. When the gates open, each bird decides for itself: fly out into the open sky or stay home. They get no penalty or reward either way.

Among these birds at the time of Massen’s study were 17 pink-and-grey Galah Cockatoos that, in the wild, fly long distances to find seeds. The Galahs chose to fly for almost every 20-minute period offered, Massen and his colleagues reported in a paper published in *Behaviour*.

Their consistent choice to fly is “in line with the notion that the birds found

flight rewarding,” says Michael Mendl, an animal behavior researcher at the University of Bristol in England, who was not involved in the study. The only exception was a pair of birds that skipped flying once, on a day when they had just been given new nest boxes, Massen says: “they had other activities to attend to”—such as courtship and mating—“which are also considered joyful.”

After flight sessions, the Galahs foraged, scratched and raised their crests more—behaviors the researchers interpreted as signs of “positive excitement resulting from free flight.” And in a test designed to measure optimism, the Galahs grew more hopeful of finding their favorite treat (a walnut) when they’d had several days of free flight and more pessimistic about their walnut prospects after several days of being grounded.

The birds’ hormones did not change after flight as predicted, however; an

expected dip in the stress hormone cortisol might have been masked by a rise caused by physical exertion, Massen says.

We can't be certain about whether wanting to fly and liking the experience add up to feeling happy, Mendl notes. Animal-cognition scientists have typically been extremely hesitant to ascribe

feelings or desires based on animals' behavior, but researchers have become increasingly open to attributing such conscious experiences to animals when the data support it. If birds are capable of conscious experience, Mendl says, "the findings would indeed suggest that the birds enjoyed flying."

For Galahs, Massen says, flight ap-

pears to be "an ethological need": a behavior they're naturally driven to perform. Massen sees his study as part of a broader shift in animal-welfare science away from simply preventing suffering and toward designing environments that let animals express the natural behaviors that seem to make them feel good. —Clarissa Brincat

BIOLOGY

Deep-Sea Survivors

Giant marine crustaceans withstand extreme starvation through a hijacked bacterial gene

WHEN SCIENTISTS REFER to the deep sea as Earth's most alien environment, they're not exaggerating. Among the cast of bizarre characters are enormous armor-covered crustaceans with large triangular compound eyes and long antennae. Researchers have long wondered how these strange creatures pull off one extreme feat: surviving more than five years without food.

It turns out that millions of years ago these deep-sea isopods most likely co-opted a gene from bacteria that—paired with a large stomach—lets them gorge on rare meals and slow their metabolism to endure long-term starvation in the ocean depths. "This is surprising because bacteria and animals are very different, and such [gene] transfers are rare," says Jianbo Yuan, a marine biologist at the Chinese Academy of Sciences' Institute of Oceanology and co-author on the new research published in *Cell*.

Giant marine isopods, which are related to garden pill bugs, live across a wide range of ocean depths, from a comparatively shallow 170 meters to the deep, dark sea around 2,100 meters

A supergiant deep-sea isopod can go for five years without eating.



down, where food and light are scarce. Some deep-sea isopods are supergiant, reaching up to half a meter in length. To understand what separates the deep-sea species from their shallower cousins, the researchers sequenced full genomes from specimens found at 300 and 800 meters and compared their energy demands, enzyme activity and oxygen use.

They found a key gene called *ND1* expressed much more strongly in the deep-sea isopods that looked more like a gene found in bacteria than in an animal: it lacked filler genetic segments called introns and produced very tiny proteins, both signs of a bacterial gene. The researchers theorize that more than 16 million years ago genes from bacteria living in an isopod's stomach may have been incorporated into its genome in a way that was then passed along to future generations.

The many copies now in deep-sea isopods' genomes seem to slow down energy production when the creatures are in cold conditions. Inserting the gene into zebra fish, nematode worms and human cells, the researchers found, lowered those organisms' metabolic rates, too.

The finding "opens a completely new window to study the evolution of deep-sea gigantism and the role of microbiome in deep-sea adaptation," says Torben Riehl, a marine biologist at the Senckenberg Ocean Species Alliance in Frankfurt, Germany, who was not involved in the study. Deep-sea ecosystems cover more than 50 percent of Earth's surface and are vital to the planet—so every little bit we learn, Riehl adds, may help us understand the benefits these ecosystems provide and how to preserve them.

—Saugat Bolakhe

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Grasping the World

Google DeepMind is betting that its Gemini AI model can control many different robot bodies—if it can first master the dustpan **BY ADAM ROGERS**

WHEN KANISHKA RAO WAS A KID, robots like the droids from *Star Wars* and Rosie from *The Jetsons* got pretty far into his head. And now that he's a principal software engineer at Google DeepMind, Rao is trying to get pretty far into theirs.

Rao remembers those bots as “helpful around the house but also sassy.” Today, in an office surrounded by galumphing, fidgeting robots of all kinds, Rao and DeepMind are trying to at least make them helpful. Any chatbot can simulate sass; Rao's aiming to build general-purpose intelligence that can inhabit many different robot bodies—in pursuit of what roboticists call “physical AI.”

In late July, DeepMind showed off its latest attempt, Gemini Robotics 2. The previous generation controlled person-shaped robots mostly from the waist up, but the new software can control whole-body movement—legs, torso, arms, fingers. It works across machines ranging from two-armed research platforms to Aptronik's Apollo 2 humanoid, letting robots fetch snacks on command, change lightbulbs, tie knots. They're not our robot overlords yet, but they're starting to act like robot servants.

The lightbulb is almost beside the point. DeepMind is trying to bring to robotics one of the tricks that make large language models so powerful: feed a model enough data that what it learns in one place still works somewhere else. Here that means carrying a skill from one job, or even one kind of robot body, to the next.

Google is hardly alone in chasing this possibility. The capital and enthusiasm sloshing through artificial intelligence have spilled over into robotics. A bullish 2025 Morgan Stanley report projected a humanoid market worth upward of \$5 trillion by 2050; Elon Musk has made Tesla's Optimus humanoid a primary focus of the company. BMW has deployed humanoid robots in one of its factories. China, meanwhile, is packed with robot start-ups; one called Unitree is launching a \$900-million IPO, having run several of its newest models through U.S. certification about a month before the Federal Communications Commission barred new foreign-built humanoids and robot dogs from the

country. An extraordinary amount of money, and now a fenced-off market, is riding on machines that still struggle with everyday chores.

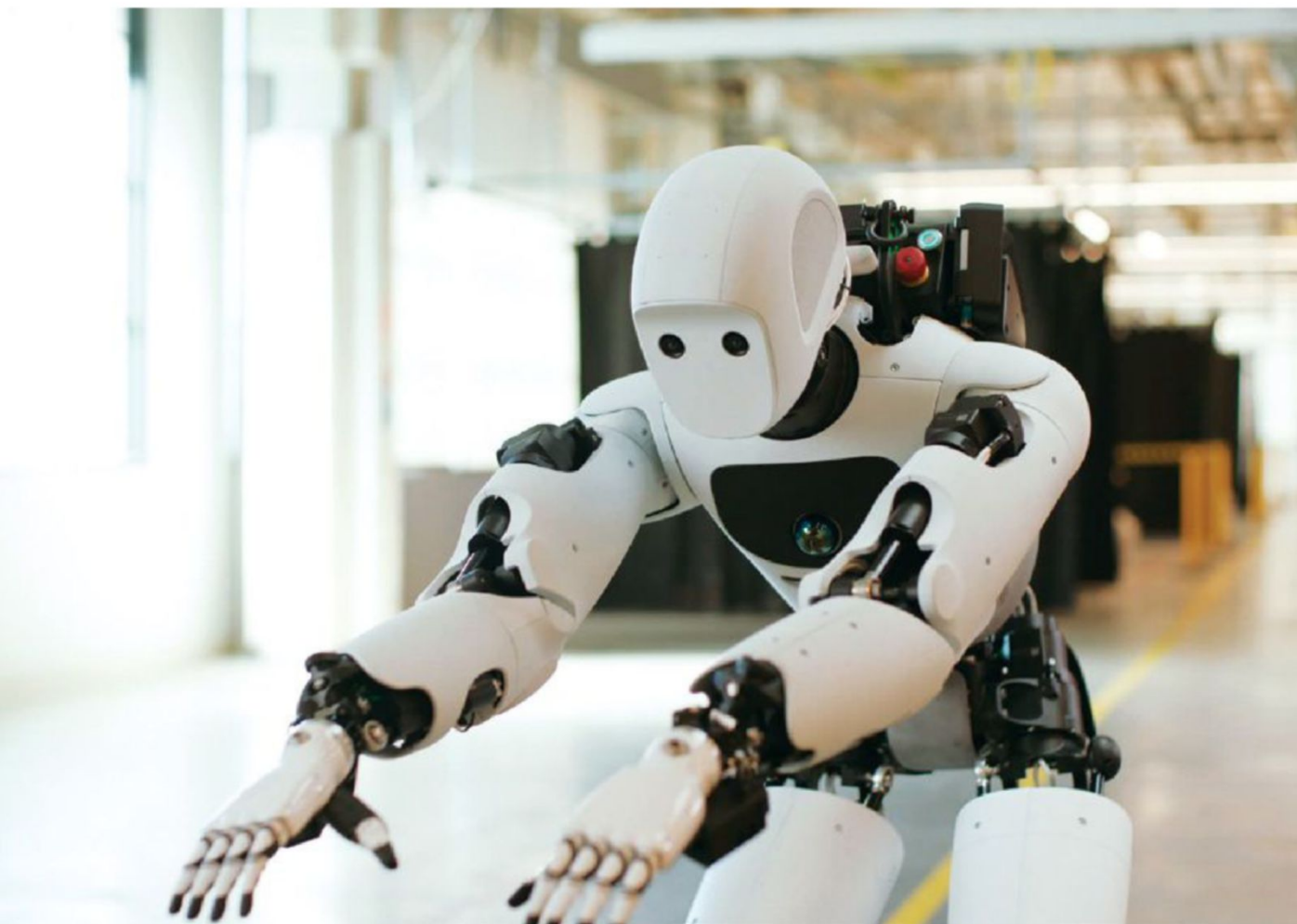
A lot of that money hinges on “dexterous manipulation.” The robots you've seen doing backflips or kung fu have mastered their own gross mobility. Folding laundry or making scrambled eggs means mastering everything they touch. “The key distinction between the backflips and the eggs is this: One of them requires you to deeply understand yourself, your own body,” Rao says. “The other one requires you to understand the world.” That, he says, “is why manipulation is so hard. It's about how you interact with the world.”

A DECADE AGO PEOPLE BUILDING ROBOTS didn't talk about “training” the way they do now. Robots were machines capable of complicated sets of motions, useful mainly in highly constrained environments such as automotive assembly lines or specific parts of warehouses. The algorithms that controlled the actions of robotic arms or bodies worked fine—until someone tried to put a robot into any of the messy, unstructured, unpredictable spaces we humans have built for our bodies and ourselves. Then the robot became just another dangerous piece of machinery. “The physical space sometimes needs to be precise to, like, centimeter, millimeter precision because they're not intelligent,” says Carolina Parada, vice president and head of robotics at Google DeepMind. “All they're doing is repeating motions.”

Machine learning offered a way around all that painstaking instruction. Instead of specifying every motion, roboticists could effectively turn the machine loose and let it work out what to do on its own. DeepMind had already made its reputation this way with AlphaGo, the system it built to master the fiendishly complex board game Go. AlphaGo initially learned from thousands of games played by humans, then improved by playing versions of itself repeatedly, using reinforcement learning. Google acquired DeepMind in 2014; the next year AlphaGo beat European champion Fan Hui, and a year after that it de-

Adam Rogers

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feated Lee Sedol, one of the game's great players. In 2023 Google combined the division with the Google Brain Team to create Google DeepMind, the organization that would build Gemini.

Today reinforcement learning is one way to get a robot to acquire new skills: Let it try to do the thing, whatever it is, in the environment where it'd have to do it (or a digital simulation), over and over. Whenever it does the right thing, it gets a little numerical reward. "It's a massively powerful paradigm because you no longer have to show it how to do the task," says Matei Ciocarlie, a roboticist at Columbia University. "But it takes a very long time."

There's a quicker way. Humans can "demonstrate" the right movements, often by teleoperating the robot or using GoPro-like cameras to record themselves performing the task—the gig worker's-eye view of the job. Simulation can add still more examples. This "imitation learning"

approach gives data-acquiring robots a leg up (if they have legs), although it also has the disadvantage of humiliating us human meat bags while we train our replacements.

But imitation learning is predicated on the robots' digital brains being able to fit the data into the context of their own bodies and capabilities. The robot has to be able to emulate a human's demonstration with its own peculiar collection of joints. Sounds hard, but engineers working on this project have an analogy: language. Train a big enough model on enough varied data, and it can pick up patterns that transfer to things it was never explicitly taught.

"We have an existence proof that a general-purpose model can control different robot morphologies because that's what humans do. If you drive a car, once you're proficient it feels like an extension of yourself," says James Marshall, director of the Center for Machine Intelligence at the University

Gemini Robotics 2 controls Appteronik's Apollo 2 from feet to fingertips as DeepMind tries to make its AI work in a humanoid body.

of Sheffield in England. (He's also co-founder of Opteran, a company that's taking a whole other path—reverse engineering insect brains.) “So it's not surprising that there could be a general technology that could control different morphologies. But moving from a quadruped to a humanoid or to a drone is more challenging and data-intensive because we don't have a full understanding of how the brain solves that problem yet.”

Gemini was already multimodal—a model family built with a knack for extracting useful information from words and images. And, of course, Gemini has already seen an absurd amount of the Internet. “There's a lot of information Gemini already has about how the world works,” Parada says. But “vanilla Gemini models don't know what it feels like to translate it into action. What we're doing is teaching them.”

So when one Googler sends a toddler-size bot to fetch a bag of popcorn

motion and still fail its overall objective.

Eventually the robot does bring the popcorn back to the researcher. He has to kind of pry it from the robot's cold, unliving pincer, but it mostly works. DeepMind reported 57.4 percent accuracy on the progress-classification test, which is better than the results from the models it tested against but nowhere near omniscience.

The DeepMind researchers know they're not quite there yet. “Our bet is that if you give [the robot] enough data, intelligence will emerge. That's the same for language and for motion,” Rao says. “With enough data of the robot interacting with things around it, it will build this implicit thing such that it'll be able to deal with generalizing to dexterous tasks.”

They've also focused on safety, with protections intended to keep bots from accidentally hurting nearby humans—by having ER 2 bring a robot to a safe stop if someone gets too close, for ex-

grapes into a plastic bag. In DeepMind's own tests, Apollo pulled off the dustpan task just 32 percent of the time. In engineering terms, the bag and the brush bristles are “deformable”; the grapes are simply fragile. The robot has to manipulate objects that fold, bend and bruise.

That's especially important because this type of system, a so-called vision-language-action model, relies on visual input. These robots see a lot—they have more cameras than you or I have eyes—but as far as the Gemini model is concerned, they feel literally nothing. A robotic hand can have 22 degrees of freedom—that's 22 independent ways to move—and still have almost no sense of what it's touching. When a Gemini-powered robot lifts those grapes, it gets no fingertip sensation telling it when one is beginning to burst. When it picks up a wine glass, it can't “feel” how much pressure the glass can take before it shatters or perceive the minimum amount of pressure to exert so that the glass won't slip through its fingers. Even if we humans aren't conscious of it, we have tactility and motor coordination wired into not only our brains but also our distal neurons and muscles, tendons, joints and digits. The digital digits don't have our evolutionary advantages. “Humans are able to get feedback much sooner and be much more reactive,” Parada says. “That is part of what we're constantly trying to improve.”

Cutting-edge robot hardware often uses strain gauges and torque sensors to supply exactly that kind of feedback, but then there's another issue. “The Internet has massive amounts of visual data—gigantic amounts—and it has essentially no tactile data or force data or proprioceptive data,” says Ciocarlie, who also co-founded the robot-hand company Tangent Robotics. Any given real-world task has both semantic and somatic elements. The tasks DeepMind has its models and robots working on are in some ways more intricate than

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An extraordinary amount of money—and now a fenced-off market—rides on machines that still struggle with everyday chores.

from a nearby lounge—Google is famous for good snacks—think of what's actually going on behind that bot's eyes, in an entire stack of software. A higher-level reasoning model, Gemini Robotics ER 2, can break down a verbal request to get popcorn into a series of steps; a lower-level model turns what the robot sees and is told into the movements needed to carry the steps out, updating predictions of what's going to happen next four or five times every second. ER 2 also watches the task unfold and estimates its progress, classifying each moment into one of five ranges of completion. That sounds almost comically basic until you consider how often a robot can execute a perfectly reasonable

ample. The company also created a new benchmark called Asimov, after the science-fiction writer who famously created three laws to govern robot behavior, which suggests DeepMind is worried about on-purpose hurting, too. Gemini, though, provides one layer of safety; the robot bodies generally come with protections of their own. Texas robotics company Apptronik installs all kinds of sensors and safety systems into its Apollo to stop it from doing anything catastrophically stupid.

In one Google video, a humanoid robot with a stylized face haltingly brushes detritus from a countertop into a dustpan. In another, a robot puts

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JOIN A JOURNEY TOWARD THE NATIONAL DAY OF CONNECTION

November 12, 2026

We live in one of the most connected times in history. Yet chronic loneliness and social isolation touch people of every age, background, and community. This is an epidemic linked with heart disease, stroke, dementia, depression, addiction, and more.

For readers of this magazine, none of that is news. Far less attention has gone to what comes after the evidence: the work of turning awareness into shared responsibility, and bringing together the people already doing it.

The Cost of Loneliness Project exists to inspire intentionally created cultures of connection in every community, ensuring every person feels valued, prioritized, and seen.

1 in 2

American adults experience measurable loneliness. *(Surgeon General's Advisory)*

\$460 Billion

The annual cost of chronic loneliness to U.S. employers from healthcare costs, sick days, absenteeism, and turnover. *(Foundation for Social Connection/Cigna)*

~100

People in the world die every hour due to chronic loneliness and social isolation. *(WHO Commission on Social Connection)*

WALKING TO THE NATIONAL DAY OF CONNECTION

This fall, Founder Lucy Rose will walk from California to New York, listening to how loneliness shows up in daily life, and inviting communities along the way to share their own stories of connection.

The walk leads to the **National Day of Connection on November 12, 2026**, a day for everyone to connect authentically: a starting point for the lonely, a way for supporters to show up, a shared moment for institutions to strengthen belonging. Like the walk itself, it's a spark, not a finish line, toward a society intentional about connection every day.

HOW TO PARTICIPATE:

Take 12 Minutes At 12 P.M. On The 12th

You don't have to wait, or walk across the country, to take part. On November 12, pause at 12 p.m. for 12 minutes to connect with someone: call a friend you've lost touch with, sit with a coworker at lunch, check in on a neighbor. Intentional moments are how this movement is built.

Bring The Day Into Your Institution

Many of *Scientific American's* readers convene people for a living. Hospitals, campuses, agencies, and companies can observe the National Day of Connection together as one shared moment, on one date, in a place where people already gather. Visit the site to take part.

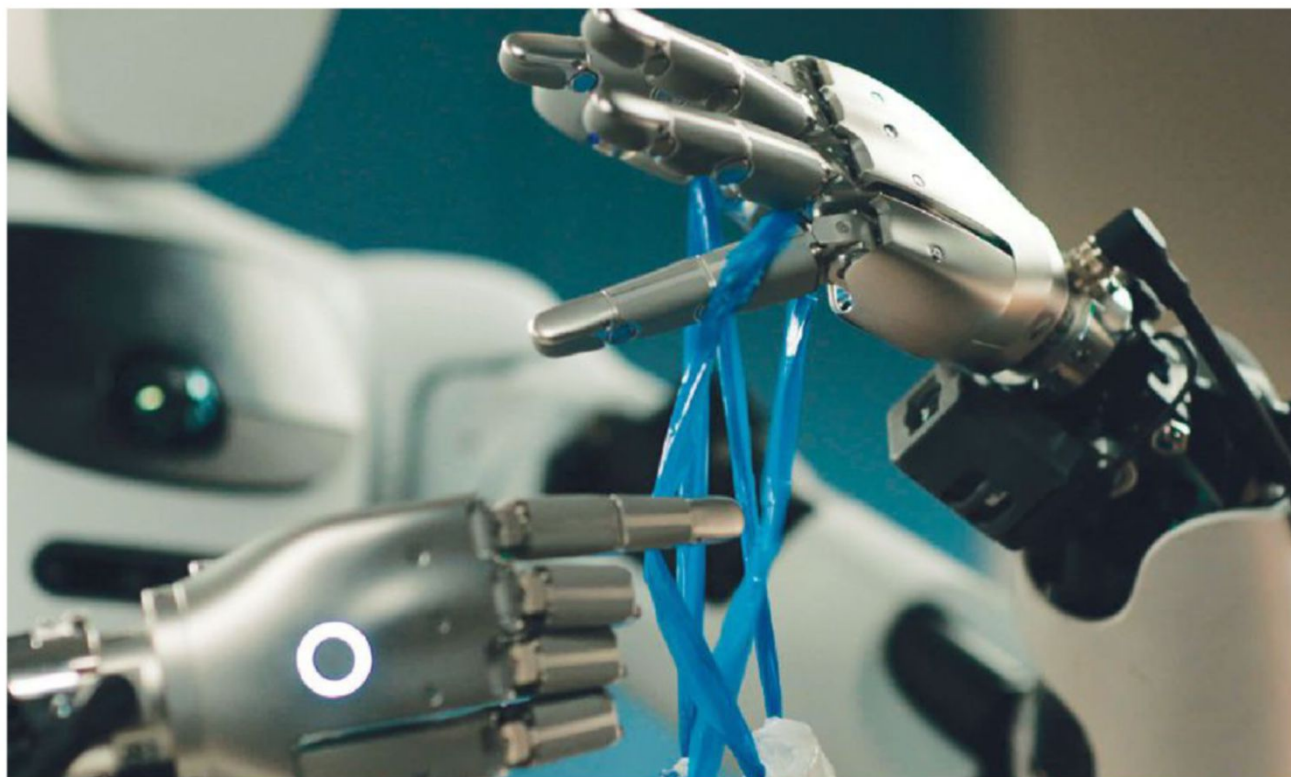


JOIN OUR MOVEMENT

Walk with Me and the **National Day of Connection** invite individuals, organizations, schools, employers, healthcare leaders, policymakers, nonprofits, and businesses to help build a future where people feel seen, included, and connected.

Visit thecostofloneliness.org/contact and follow @thecostoflonelinessproject to get involved.





Continued from page 24

plenty of jobs robots already do reliably. But the tasks DeepMind bots can do still don't require human levels of dexterity, Ciocarlie says—"the kind of things where the semantic, conscious intelligence needs to be supplemented by motor intelligence."

Much of the new money in robotics is chasing machines that are person-shaped. This goal makes some sense; a machine that moves around on caterpillar treads and has 20 multi-degree-of-freedom tentacles bursting from an eight-foot-tall torso might be better at getting places and carrying stuff, but it would be perhaps *less* capable of operating in an environment built for humans, where, for example, countertops are usually about 25 inches deep and doorways are about 36 inches wide. Ironically, imitation learning has a reinforcement effect here, too. If a human is demonstrating or teleoperating a task, the robot is more likely to learn it if its own parts aren't too different from the human's—you want that "embodi-

ment gap" to be as small as possible. It's as if future robots will inherit technical debt from evolution itself.

The term "embodiment" carries philosophical baggage, and here the irony doubles back. For decades proponents of the idea of embodied cognition argued against disembodied intelligence. Understanding, in this view, depends on having a body that moves through and responds to the physical world. (Another approach to robot control called a world model—touted by chipmaker Nvidia, among other laboratories—leans heavily on this idea.) By this logic, knowing what an apple is takes a lot more than a calculation of how the word "apple" relates to other words in a multi-dimensional vector space. It's the fruit's feel, its smell and taste, and a person's preference for Galas over Fujis.

It might be true. But Rao, at least, isn't convinced. "Before I joined robotics, I was on the speech-recognition team, and I used to work on language modeling. I thought this would be true where surely you can't know what an

Tying a trash bag is a deceptively hard test of the dexterous manipulation robot hands need for everyday chores.

apple is until you've held an apple and tasted it," he says. "I think I was totally wrong. It's been the other way around. It's the digital AIs that have really made the physical AI more powerful. It seems like you don't need to touch all these objects or interact with them or see what they weigh to understand them."

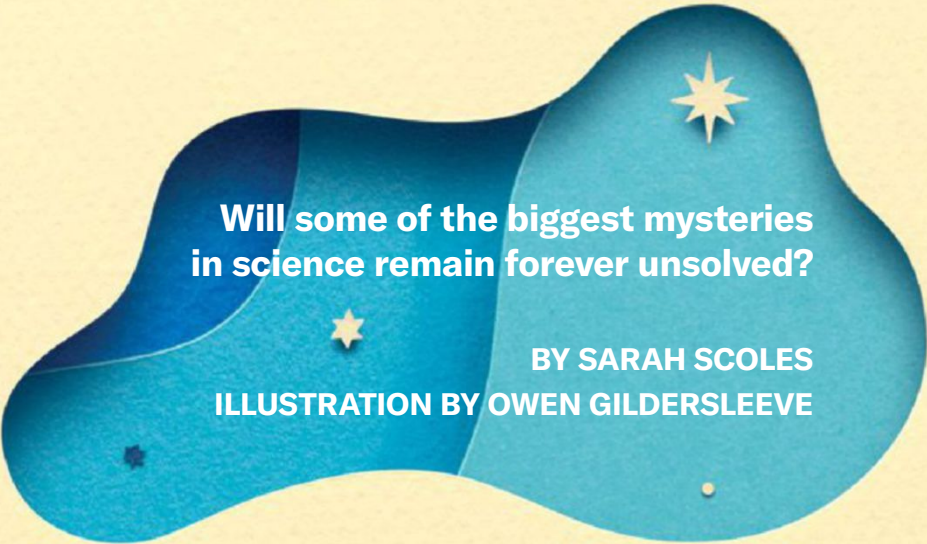
About five years ago D. E. Wittkower, a philosopher at Old Dominion University in Virginia, borrowed philosopher Thomas Nagel's 1974 question about the inner life of a bat for an essay called "What Is It Like to Be a Bot?" DeepMind's robots suggest almost the opposite question—or at least ask a different one: Who cares? Maybe the machine does not need anything remotely like our experience of an apple to know enough about apples to handle one. Maybe these robots don't need an inner life. But they could use some nerve endings. ●

SPECIAL REPORT

IMPOSSIBLE QUEST



SIBBLE IONS



Will some of the biggest mysteries
in science remain forever unsolved?

BY SARAH SCOLES
ILLUSTRATION BY OWEN GILDERSLEEVE



SCIENCE, AT ITS BEST, IS A STRIVING TOWARD TRUTH. It is not, although we often think of it as such, the search for absolute truth. It's more a process of systematically gathering and interpreting data about the universe to understand its past and present and predict its future. What results is the best approximation we can access at any given time with the information, methods and instruments we have.

And what counts as the best approximation of truth often changes. Isaac Newton began to devise his apple-falling theory of gravity in 1666. It worked well for everyone's purposes in the 17th century. Then about 250 years later Albert Ein-

Alexander Krauss's most recent book, *The Engine of Scientific Discovery*. Until radio antennas existed, for instance, astronomers didn't know the universe emitted radio waves, so they didn't wonder what powered the gigantic jets shooting at nearly light speed from the centers of galaxies. Before microscopes, biologists didn't know about animalcules, as microbes were first called, so they didn't know they might someday study how the microbiome impacts mental health. "When scientists invent novel instruments and new computational and experimental techniques, they effectively expand the sensory and cognitive reach of science itself," Krauss says.

Not all questions will find answers. Some will likely remain beyond scientific grasp, even with methodological and interdisciplinary advances.

stein stepped in with a better approximation: the general theory of relativity. Today some scientists are working to find ways to unite relativity with quantum mechanics, seeking a new approximation of the "truth" of gravity.

But are there some questions science can *never* fully answer? There are certainly questions scientists can't answer *yet*. There are also queries scientists once thought impossible to resolve that weren't. In 1835, for instance, philosopher Auguste Comte asserted that humans could never know what stars are made of. Then came spectroscopy, which allowed astronomers to parse stellar light for fingerprints of different chemicals.

Most things that seem forever unknowable eventually fall out of that porous basket. New ways of thinking or measuring expand the boundaries of science. This idea is the thesis of scholar

Still, not all questions will find answers. Some will likely remain beyond scientific grasp, even with methodological and interdisciplinary advances. Some will be so beyond our imagination that they will remain unknown unknowns forever. That's frustrating: science aims to understand the universe by observing, experimenting, interpreting, iterating. But that enterprise hits walls when there is nothing to observe or experiment on, when something lies past a fundamental barrier, or when observing or experimenting changes what is being observed or experimented on.

So how do we make sense of, and make peace with, necessary gaps in our knowledge? Perhaps by accepting that science isn't about finding the truth, the whole truth, and nothing but the truth. We'll just have a set of evolving best shots and, ideally, shots that keep leading—like a non-Brownian walk—to the next destination. ●

Sarah Scoles

is a Colorado-based science journalist and a contributing editor at *Scientific American*. Her newest book is *Countdown: The Blinding Future of Nuclear Weapons* (Bold Type Books, 2024).



Scientists once doubted we'd ever know what stars are made of. This deep-field image from the James Webb Space Telescope shows stars and galaxies in a tiny piece of the night sky.



BIOLOGY

How Did Life Begin?

Scientists disagree on how biology got started and on whether we can ever know for sure

BY SARAH SCOLES

ILLUSTRATIONS BY DEENA SO'OTEH







IN A LABORATORY AT MCMASTER UNIVERSITY IN ONTARIO, a device that seems almost alive glows purple as it churns through its work. Atop a boxy base that resembles a small kitchen island, a windowed hemispherical chamber sits. Cords and instruments poke from it like flower petals. Gas billows from its bottom. The setup's purpose is hard to fathom if you don't know what it is and even perhaps if you do. Inside that little chamber is a whole world. Its name is, appropriately, the Planet Simulator.

Maikel Rheinstädter, a professor in McMaster's physics and astronomy department, and his team can program the simulator to mimic many different environments. They can swing it through temperatures from below freezing to past boiling, change the ingredients of the tiny atmosphere, create rain and then dry it up, and shine light ranging from ultraviolet to infrared, as different stars would. In the chamber's center, a drop of water on a chip contains the chemistry of whatever earthly era or exoplanetary site the group is trying to re-create.

The scientists are watching to see what might grow in that little bit of liquid—to determine which ingredients and conditions can produce life's building blocks, get them to stick together, and maybe someday bring something to life. If it can do that, the Planet Simulator could help answer one of the biggest questions of all: How did life start on Earth?

But whether any scientists, even with whole small worlds under their command, can definitively find the answer to that question is another matter. Can we truly know the origins of our planet's life, or will we at best be able to find only plausible possibilities? This larger query remains an open question. After all, the natural experiment that first produced life is

not reproducible, no matter how fancy labs become.

SOME QUESTIONS are human classics, asked for millennia and more. Why are we here? Are we alone? What happens when we die? Where did we come from? In some way, all those quandaries are behind the one Rheinstädter is pursuing: What is life, and how did it—we—get here in the first place?

In some traditions, the answer is spiritual. Creation stories are, after all, fundamental to most religions. There is even a kind of scientific creation story, a theory of life called spontaneous generation, most prominently proposed by Aristotle more than 2,000 years ago. Spontaneous generation is the idea that life can *poof!* arise from not-life: carcasses or trash beget maggots; scallops and clams grow in sandy spots. That thinking dominated for millennia, until Louis Pasteur sterilized some broth in 1859 and placed it in a glass container. When he cut the liquid off from outside contamination, nothing grew. But when the outside world was allowed in, the broth became quickly cloudy—teeming with microbes. Pasteur's experiment implied that being alive is hereditary—life, not *not*-life, begets life.

But if that were the case, something still had to be the first alive thing. In

that earliest instance, then, the idea of spontaneous generation isn't actually so far off: at some point, the chemical and physical did have to unite in such a way that they became biological. "When you learn about biology in school, it's taught as this completely different discipline than something like chemistry or physics," says Harrison B. Smith, a complex systems and astrobiology researcher at Tokyo's Earth-Life Science Institute. "But we have to remember that biology emerged still subject to the same constraints of chemistry and physics."

Just when it emerged, and how, is tricky to pin down. Despite decades of increasingly complex research, a 2020 review noted that a then 45-year-old proclamation was still true. "It must be admitted from the beginning that we do not know how life began," chemists Stanley Miller and Leslie Orgel wrote in their classic 1974 book *The Origins of Life on the Earth*.

Miller had conducted an experiment in the 1950s showing that if he simulated the chemical conditions of the early Earth—in a proto-version of the Planetary Simulator—and hit the chemicals with electric sparks, organic molecules started to form. "It is generally believed that a variety of processes led to the formation of simple organic compounds on the primitive earth," the

quote continues. “These compounds combined together to give more and more complex structures until one was formed that could be called living.” But, the authors added, “No one should be satisfied with an explanation as general as this.”

And scientists aren’t.

THE POSSIBLY NEVER-ENDING QUEST toward an explanation is the purview of a scientific field called Origins of Life, or OoL (a word that seems like it would be a good name for the first-ever organism). Little in this field is known for certain. There’s general agreement on relatively few points and much contention and competition about others.

As far as consensus goes: Earth’s oldest fossils date back to at least 3.4 billion years ago, with evidence that life may have arisen more than half a billion years before that. Scientists also generally agree that life didn’t come into being in single flash but in an extended sequence. Over time chemical reactions produced early versions of metabolism, the ability for molecules to pass down information, and the formation of compartments that would become the boundaries of cells.

That’s about it, though, in terms of what’s known. For the rest, scientists can’t even agree on the right way to approach open questions. Some research-

ers take a top-down tack, looking at what modern organisms have in common, such as cell-based structure, DNA and RNA, and specific energy molecules. Those commonalities, the thinking goes, probably stem from properties fundamental to the earliest life.

Other scientists go bottom-up, mimicking in a lab what Earth’s envi-

which you can’t even see in the viewfinder,” he says. “And I thought, ‘Well, I’ll do Jupiter. You can’t miss that.’ ” After measuring methane above Jupiter’s clouds, he became interested in planets’ atmospheres and eventually the climate of early Earth.

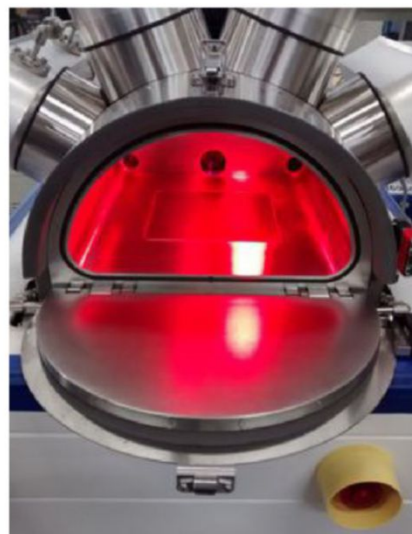
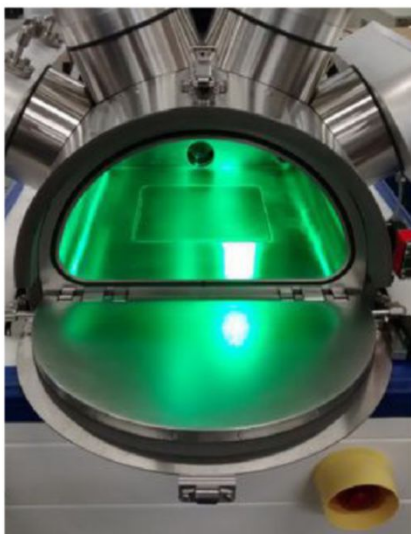
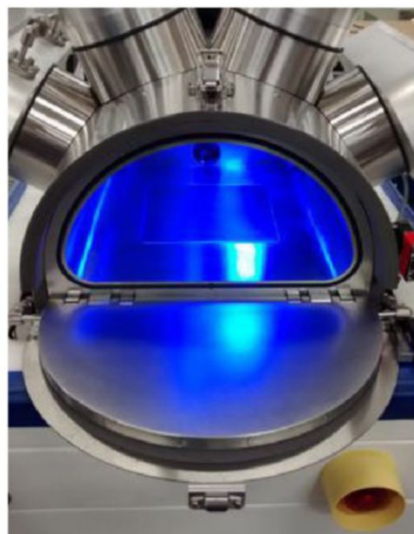
At first, Catling wasn’t sure he had much to contribute to OoL work. “I’m

Some questions are human classics.
Why are we here? Are we alone?
What happens when we die? Where
do we come from?

ronment might have been like billions of years ago to try to produce the complex chemistry that became biology, as Miller and Rheinstädter have done. In this approach, scientists don’t assume that modern life much resembles early life. Rather modern biochemistry may be largely the result of evolution.

David Catling of the University of Washington is a scientist in the latter group, having come to OoL research through his studies of planets. That started early: In an undergraduate astronomy course, Catling had to come up with a telescope project. “Other people were looking at very faint stars,

not a biochemist. I’m not an organic-synthesis chemist,” he says. But, he learned, chemists needed people like him to do exactly what he was interested in: to learn more about Earth’s past. “What was plausible, what was not plausible,” Catling says. Thirteen years ago the Simons Foundation started a big origins project, and Catling jumped onboard a few years later. The private money, he says, might have doubled the amount available for OoL studies, which are sometimes neglected because they overlap disciplines. But, as the Simons project demonstrates, attempts to understand the origins of life are neces-



The Planet Simulator at McMaster University in Ontario can mimic the radiation of different stars, as well as the surface light filtered by different planetary atmospheres, to study how life might emerge.



sarily interdisciplinary, drawing together the fundamental forces and rules that shape the planet and the universe and that don't, themselves, recognize academic or social boundaries.

SCIENTISTS DON'T DIFFER just in *how* they study OoL. Their hypotheses about how life first animated itself are also in tension. These "how's" fall into two main camps, whose names seem designed to start a fight: "Metabolism First" and "RNA First."

In the latter, RNA was the initial important part of biology to form. RNA is single-stranded genetic material that carries information in the pattern of its four repeating chemical bases: adenine, cytosine, guanine and uracil. (DNA is made of those first three bases but replaces uracil with thymine and has two twisted-together strands instead of one.)

In scientists' vision of "RNA World," an early era in life's evolution before DNA or proteins existed, RNA stored information and catalyzed chemical reactions. RNA would have assembled into single strands that could make copies of themselves. That copying, by providing a way to reproduce and evolve, could have then kicked off the beginning of life. The more structurally complex DNA would have come later (in a process scientists don't yet understand) to play the major role in storing and passing down genetic information, and proteins would have taken over the chemical catalyzing.

The Metabolism First idea, meanwhile, suggests the critical first development was the ability to convert basic chemicals into more complex compounds. According to this scenario, chemical reactions happened spontaneously between elements and compounds on the early Earth. Those began simply, but some happened to produce energy-storing molecules. Those molecules started more chemical reactions, which became increasingly complex as the cycle continued. Eventually the self-sustaining chemical reactions resulted in structures resembling RNA. Or at least that's the idea.

The location of either of those firsts is the source of yet another debate. Some scientists think ground zero was in Earth's surface water: a warm little pond (an idea Charles Darwin first floated) or a hot spring; others think it may have happened in a deep-sea hydrothermal vent, although this hypothesis is falling out of fashion. The heat common to all these ideas would have spurred chemical reactions along.

Another waning idea is the guess that space rocks may have seeded life on this planet. Samples of asteroids and meteorites suggest that although they have organic molecules, they don't have the kind whose structure matches what life uses here. "Clearly, there's something different that you need for the environment, for an origin of life," Catling says. "And it worked on a planetary body like Earth, but it didn't

work elsewhere in the solar system."

He suspects the difference is that asteroids don't have the same environmental conditions found on Earth—or on the worlds inside the Planet Simulator. One example is wet-dry cycles: in a pond or on the simulator's chip, for instance, water may evaporate or freeze, leaving behind non-H₂O building blocks that then become more concentrated. Energy from the sun helps reactions between those blocks along, coaxing them to form polymers, or longer chains of molecules.

Hydrothermal vents as an origin site are also losing popularity at the moment for a similar reason, in Catling's view: surrounded by the entire ocean, famously large, vents could not have concentrated chemical constituents enough.

NO MATTER WHERE A SCIENTIST FALLS among the OoL options—which method, what first and where—there's still a fundamental problem: When researchers such as Rheinstädter re-create conditions from the early Earth, the ingredients readily assemble themselves into the simpler building blocks of life, among them amino acids or even cell compartments, which are made of fats called lipids. But getting those building blocks to stick together and interact in a lively way is a different story. "What's still very much a dark field is how those things become more complex," says Joana Xavier, an independent bioengineer and OoL researcher. Rheinstädter agrees. "I think what we have right now is that the building blocks—amino acids, nucleotides—they form very easily," he says. "Even if you step out in a puddle, you will find those."

Rheinstädter is using the Planet Simulator to figure out how to get those puddle parts to complexify themselves and, in particular, assemble into RNA. In that quest, he has a fairly radical idea: Maybe the chemistry soups researchers are creating *are* getting sufficiently complex—but scientists are missing it because they're seeking the wrong thing. "People are always looking for lab-grade RNA," he says—the kind you can order from a catalog. Perfect, in other words.

But that kind of RNA wouldn't have done well on the four-billion-year-old Earth. It's too fragile. "If you take it out of the fridge, it degrades immediately," Rheinstädter says. Maybe, he continues, that means the RNA in RNA World wouldn't have been the same as the RNA in *our* world. He came to this idea somewhat by accident, while poking around the Planet Simulator. When the simulator was set to mimic the ancient Earth, Rheinstädter and his team found that molecules *do* link up to form RNA strands of about 100 bases long. "However, they're not perfect," he says. "They have structural defects." But what they lack in prettiness they make up for in strength. "You cannot destroy them," Rheinstädter says.

He started to wonder: "What if nature didn't start off perfect?" What if, instead, it started out with a precursor version of genetic material? The RNA of today may have come later, with evolution. "Maybe it's just silly to expect that from the beginning," he says. Perhaps the mixed-up version of RNA that spews from the Planet Simulator was the kind that first bubbled up from some terrestrial pond. After all, what—besides a creation story—starts out with a fully formed version of life?

Other scientists, Rheinstädter posits, may have actually been creating this flawed RNA all along in similar experiments, unaware—because they weren't looking for it. Now the team is working on whether imperfect RNA can actually do what perfect RNA does: catalyze and transmit information.

Catling, meanwhile, is pursuing a shakeup idea of his own involving the "where" debate. He's been looking recently at what scientists call the "phosphate problem," first identified in the 1950s. The issue: Phosphate is key to many things life does and needs—the compound is part of the genome, the cell compartment and metabolism, for instance. "Yet in the environment, if you go to a river or the ocean, the level of dissolved phosphate is really tiny," Catling says.

If there's not much in the water, it's hard to understand how proto-life

could have gathered enough. But when Catling was working on the Simons project, he and colleagues found a kind of water body with plenty of phosphate: soda lakes, which are a bit like big ponds someone dissolved a lot of baking soda into. These water bodies with an abundance of carbonate and extremely high alkalinity are found around the world; the best-known examples are in Africa and North America. The calcium in them binds with carbonate (the baking soda bit), allowing natural phosphates to accumulate instead of sticking to calcium as they would in less carbonate-rich water.

The most phosphate-rich lake in the world is Last Chance Lake in Canada. In summertime, it—and most soda lakes—evaporates, leaving a crusty white landscape; as the seasons progress, they get wet and become like lakes again. The wet-dry cycle concentrates the existing phosphate. It could, Catling thinks, be precisely the type of place where chemistry and physics became biology. Maybe it would more appropriately be called First Chance Lake.

OF COURSE, NEITHER Rheinstädter nor Catling knows if their ideas represent the true "first" or "where." And scientists disagree about whether we will ever know for sure. Even if researchers can reproduce the conditions of early Earth and coax life from it, that success would represent just one way the story might have gone. Knowing for sure that it is *the way* it happened is a different story. The tape can never be rewound.

Plenty of OoL scientists, though, think that doubt is naive. After all, if cellular biology flows from physics and chemistry through a set of logical laws and processes, maybe there is only one path between the three. "A diamond forms in a very specific set of conditions. It's only in that set of conditions," Xavier says. "And the diamond is rare because those conditions happen only on those rare occasions. I think the formation of cells is exactly the same type of question."

Catling, though, disagrees. "I think

it would be a plausible answer rather than definitive." He does, though, think that looking beyond Earth could yield more certainty, in that it could help scientists understand whether the origin of cellular life is actually deterministic—that is, whether, given certain conditions, it always emerges in a certain way. If, for instance, we see it on other planets with similar environmental histories and if it has the same biochemical makeup, then researchers could infer that there's a set process by which life like ours arises.

Still, those are huge ifs: *If* there's life out there, *if* we know how and where to look for it, and *if* we find it. That's a lot of physical and philosophical difficulty to bring together. But it's also not impossible. "It's always dangerous in the history of science to say that we will never know something, because later on, people have found it," says David Dunér, a historian and philosopher of science at Lund University in Sweden.

Before the field of OoL can get close to that point, though, it needs a cultural change. At the moment, it's a fairly contentious discipline, with researchers personally invested in their versions of how and what first and where. This competition is amplified by how little direct evidence is available, Xavier contended in a *Nature* comment. To help researchers collaborate and focus on the big picture, she co-founded the Origin of Life Early-career Network, bringing together younger scientists. But schisms and heel digging are probably inevitable in such uncertain fields, Catling says.

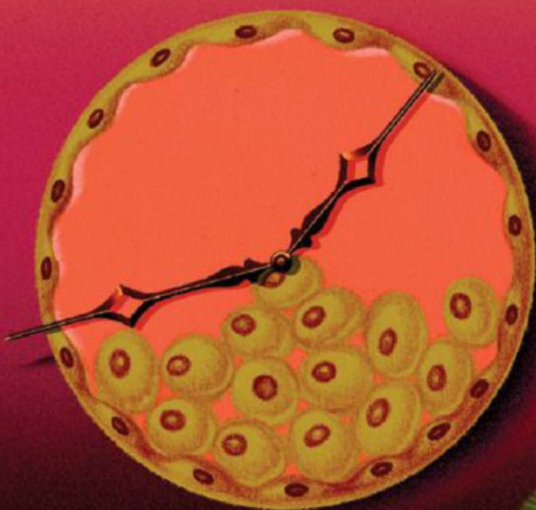
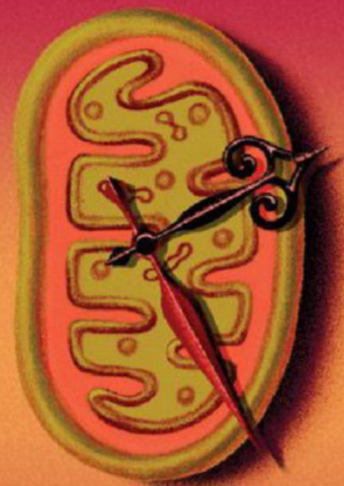
Maybe more evidence for the origin of life will come from a soda lake, or a planet simulator, or an actual planet far, far away. But at least some scientists are okay with the uncertainty about uncertainty. "I sometimes think about how lucky I am, in some ways, to exist in this moment of time when this still is an unanswered question, and how exciting it is to think about all the possibilities out there," Smith says. "I think that it will be answered, but I think it will be some time because a lot of the right questions aren't even articulated." ●



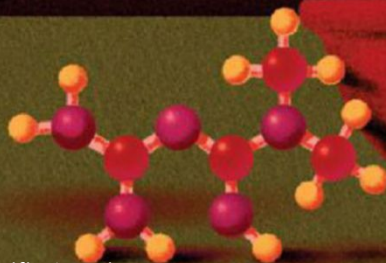
HEALTH

How Long Could Humans Live?

Scientists are pursuing the limits of longevity



BY VENKI RAMAKRISHNAN
ILLUSTRATIONS BY ADA ZEJUN SHEN





HUMANS MAY BE THE ONLY CREATURES THAT ARE aware of their mortality. There is no evidence that other animals know their time on Earth is finite. The realization that we and everyone we know will someday die must be one of the more unsettling discoveries of childhood.

Ever since humans recognized we have a limited lifespan, that knowledge has shaped our cultures, religions and philosophies. Although we make plans, pursue careers and behave as though we will live indefinitely, the fear of death and the desire to transcend it remain.

As a species, we have made some major strides against mortality. In modern times, death from violence, disease and famine has become less common than it once was. At the same time, medical advances and a dramatic decline in fertility rates have produced aging societies. The proportion of people older than 65 is rising rapidly, while the working-age population that supports them shrinks. [Understanding aging](#) is therefore an urgent practical challenge. If we can delay its effects, older people may remain healthy, independent and productive for longer.

But alongside this public health imperative is an enduring dream. A growing number of tech billionaires are funding efforts not merely to slow aging but to defeat it altogether. Their goal is [radical life extension](#) and, ultimately, something approaching immortality. But is that even possible? These efforts have scientists chasing one of the biggest mysteries of life itself: Is there a biological reason that humans must die? And if not, could we one day live forever?

THE [DIVERSITY OF LIFESPANS in nature](#) suggests that aging isn't fixed. Despite being constructed from the same chemical building blocks, species can have dramatically different lengths of life. Mayflies may live only days, mice about two years, and bowhead whales and Greenland sharks for

centuries. Galapagos tortoises live so long that one of them hobbling around today could have encountered Charles Darwin in 1835.

These differences are not random. Lifespan is closely related to metabolism. Smaller animals generally have higher metabolic rates and shorter lives; larger animals tend to metabolize energy more slowly and live longer.

Natural selection doesn't care how long an organism lives. It favors traits that increase reproductive success. Every species makes trade-offs in how it allocates resources among growth, reproduction and maintenance. A mouse doesn't improve its ability to produce more offspring by investing in longevity if starvation or predators are likely to kill it first. For a mouse, investing in rapid growth and reproduction is more advantageous. But larger animals, such as whales, mature slowly and reproduce later. Their bigger size also reduces the risk of predation, making long-term maintenance more worthwhile.

The same logic explains some notable exceptions. Birds and bats often live much longer than similarly sized terrestrial mammals because flight reduces the risk of predation and also allows them to forage over a wide area, cutting the chances of starvation. When surviving longer increases reproductive success, evolution favors slower aging.

Evolution can also reward genes that are beneficial early in life even when they become harmful later. For example, the same genes that promote rapid growth or prevent cancer during youth can contribute to aging later on. This evolutionary theory of aging is known as antagonistic pleiotropy. "Pleiotropy" simply means a gene can have more

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than one effect, and “antagonistic” means some of those effects can be harmful. The theory suggests that aging is not an adaptation in itself but an unintended consequence of evolutionary compromises. The upshot is that each species has a maximum natural lifespan.

What about us? Human life expectancy has roughly doubled over the past 150 years because of improvements in public health, nutrition and medicine. Maximum lifespan is a different matter. Even centuries ago some individuals lived remarkably long lives. Michelangelo lived to be almost 90 years old. The longest documented human life is that of Jeanne Calment, who died at 122 in 1997. No one since then has lived past 120. Under current biological constraints, humans appear unlikely to live much longer than that. Moving much beyond it would require altering the biology of aging itself.

As people age, our muscle mass declines, reducing strength, mobility and balance. We suffer from fatigue and exhaustion and have difficulty carrying out everyday activities. Chronic diseases become more common, and resistance to infection weakens. Cognitive function declines as well. These symptoms are merely external manifestations of a gradual loss of cellular and tissue function, which themselves are a result of changes and damage to the molecules of life and their regulation by our genes.

Aging was once viewed as simple wear and tear, like a machine slowly breaking down, but modern biology has revealed a more complicated picture. Cells possess sophisticated systems for repairing damage, maintaining our repertoire of proteins, recycling components and regulating metabolism. Aging occurs not merely because damage accumulates but because these protective systems themselves become less effective over time.

The hallmarks of biological aging appear in multiple body systems. They include damage or changes to our DNA, deterioration of the quality and distribution of proteins, dysfunction of mitochondria, decline in our response to external nutrients, chronic inflammation, and reductions in stem cells. These systems are deeply interconnected—a disturbance in one often affects many others.

THE ENCOURAGING NEWS is that there is no physical or chemical law preventing us from modifying these processes. The challenge is that aging is extraordinarily complex.

Among the most powerful interventions discovered so far is caloric restriction. Animals given just enough calories to maintain adequate nutri-

tion often remain healthier and live significantly longer. Caloric restriction reduces protein synthesis and stimulates autophagy, the cellular recycling process that removes damaged molecules and organelles. In species ranging from worms and flies to rodents and primates, caloric restriction produces animals that appear biologically younger than their age. The drawbacks, however, are considerable. Constant hunger, sensitivity to cold, impaired wound healing and reduced libido make strict caloric restriction difficult to sustain.

Scientists have searched for drugs that mimic some of the effects of caloric restriction without the side effects. One that appears promising is rapamycin, originally discovered in soil samples from Easter Island, also known as Rapa Nui by its native people. This compound affects a cellular pathway called TOR (or mTOR) that is involved in growth and metabolism. In mice, it extends lifespan and improves several measures of health. Yet rapamycin is also an immunosuppressant, raising concerns about infection and long-term safety. Current research focuses on whether lowering

Human life expectancy has roughly doubled over the past 150 years.

the dose or synthesizing chemical analogs of rapamycin can produce its beneficial effects without the problems.

Metformin, a widely used diabetes drug, has likewise attracted interest. It acts on a protein in mitochondria involved in respiration, which indirectly influences caloric-restriction pathways. Evidence for benefits in healthy individuals, though, is mixed. The recent GLP-1 drugs developed for diabetes and obesity also appear to have beneficial effects on multiple organs, including the brain. Yet they, too, have side effects, including muscle loss. For use as antiaging therapies, both metformin and GLP-1 drugs will require careful clinical trials.

Another major target of antiaging science is cellular senescence. Cells experiencing damage or stress sometimes enter a senescent state in which they stop dividing and begin secreting inflammatory molecules. Early in life this response is beneficial, aiding development, wound healing and cancer prevention. With age, however, senescent cells accumulate faster than the body can remove them.

The resulting inflammation contributes to tis-

sue dysfunction throughout the body. In mice, eliminating senescent cells can improve many features of aging. This finding has sparked intense interest in so-called senolytic drugs designed to remove such cells selectively. Several candidates are now being tested against age-related diseases such as osteoarthritis and fibrosis. Apart from making sure the drugs are safe, the challenge is achieving the right balance: senescent cells serve a biological purpose, and eliminating them indiscriminately could lead to new problems.

Another, somewhat bizarre experiment has raised the prospect of a different antiaging strategy. In a process called parabiosis, researchers physically joined pairs of rats so they shared circulatory systems. Old rats paired with younger ones outlived those paired with animals their own age. Such findings went on to inspire a slew of companies offering transfusions of plasma from young donors. There is no convincing evidence that such procedures slow aging in humans. Nevertheless, the work has set off a major search for factors in blood that change with age and may eventually prove therapeutically useful.

MOST OF THESE APPROACHES aim to slow down aging. A more radical goal is to reverse it.

This possibility emerged from a series of discoveries, spanning decades, involving the cells of the early embryo, which possess remarkable flexibility. These so-called pluripotent stem cells can generate any tissue in the body. In later stages, the stem cells become progressively more specialized, and each class generates specific types of tissue such as nervous system cells or blood.

In 1958 British biologist John Gurdon showed that the nucleus from a cell in a tadpole could be transplanted into an egg cell to create an entirely new frog. Later, in 1997, Dolly the sheep served as a demonstration that cloning was possible in mammals. The exact process for reverting adult cells back to an early embryonic stage, however, wasn't clear.

A major breakthrough came in 2006, when Japanese biologist Shinya Yamanaka discovered that activating just four genes could convert adult cells into pluripotent stem cells. These Yamanaka factors effectively induce cells to return to an earlier embryonic stage by genetically reprogram-



ming them. The discovery raised the possibility that if we can reset cellular age, perhaps we can reverse aging itself.

Applying the full reprogramming process to an adult organism would be dangerous because the resulting pluripotent cells could form tumors known as teratomas. Researchers therefore began exploring partial reprogramming, briefly activating the Yamanaka factors in ways that appear to rejuvenate cells while maintaining their specialized identities.

Results in mice have been striking. Treated animals often show improvements in tissue function and markers of biological age. In one experiment, scientists reportedly regenerated a damaged optic nerve by injecting Yamanaka factors via a viral carrier into the eye. Researchers are now conducting clinical trials to see whether the procedure can reverse degeneration in the retina or optic nerve.

Yet formidable obstacles remain. Current methods typically rely on gene-delivery systems that are not ideal for widespread human use. Reprogramming is often uneven, affecting clusters of cells and leaving others in the same organ unchanged. Different organs age at different rates and may require specific targeting. Researchers are pursuing safer and more controllable methods, including small molecules that might produce reprogramming without the introduction of new genes.

Despite these challenges, cellular reprogramming represents the most compelling route yet toward genuine rejuvenation, rather than merely slowing decline.

EVEN IF SUCH INTERVENTIONS SUCCEED, translating them into medicine will be difficult. Antiaging therapies face a higher bar than treatments for life-threatening diseases. Patients with advanced cancer may accept substantial risks in experimental medicines because the alternative is death. Healthy individuals are unlikely to tolerate serious side effects from drugs they may have to take for decades. And clinical trials present another obstacle. Regulatory agencies generally approve therapies for specific diseases, not for aging itself. As a result, scientists often test antiaging interventions indirectly through research on age-related disorders.

Much antiaging research is motivated by the idea of extending “healthspan”—the number of healthy years we enjoy—without necessarily extending lifespan. According to this philosophy, people should aim to remain healthy and independent for longer and then experience a relatively

brief period of decline before death. It is an attractive idea, but there is little evidence that it’s possible. In many countries, people are living longer, yet the fraction of life spent with multiple chronic illnesses has increased. On the other hand, there are striking differences between individual countries in the proportion of life spent in good health. People in Sweden, for example, have a considerably shorter period of late-life disability than those in the U.K. Such differences suggest that

Most antiaging approaches aim to slow down the process. A more radical goal is to reverse it.

public health policies, lifestyle factors and medical care can influence not only how long we live but how well we live.

Ultimately, though, will any of these findings allow us to significantly extend the human lifespan? There is no scientific law against the idea, but nor is there any reason interstellar travel must be impossible. It’s just that the practical complexities are immense. Aging involves countless interacting processes operating across cells, tissues and organs. Extending lifespan dramatically would require mastering many of them simultaneously. It is unlikely that a single intervention could simply switch aging off without affecting us in other ways.

In the meantime, as we await major medical advances, basic strategies allow us all to play the antiaging game on a personal scale. Scientists know a moderate diet with a healthy intake of fruits and vegetables affects caloric-restriction pathways. Much of our body’s repair and recycling work is carried out during our sleep cycle, and exercise helps to regenerate tissue, including muscle and mitochondria. For now, the best-supported tools for healthy aging remain the trio of diet, exercise and sleep. In addition, there is good evidence that avoiding social isolation and having a sense of purpose are associated with better health and longevity.

As long as accidents, natural disasters, disease and wars can kill us, true immortality is out of the question. And living for hundreds of years is unlikely anytime soon. Instead we can think of life as an eternal banquet that individuals enter and eventually leave. We should consider ourselves lucky to be part of it at all and enjoy the feast while we can. ●



PARTICLE PHYSICS

What Is Dark Matter?

**More experts than ever think
we might never know
what it really is**

BY JOSEPH HOWLETT



Photomultiplier tubes in the XENONnT experiment at Italy's Gran Sasso National Laboratory search for signs of dark matter particles interacting with liquid xenon.

USED TO HAVE A MORE INTERESTING MORNING COMMUTE. At daybreak I'd squeeze into a tiny Fiat with all the physicists it could fit. We'd drive through winding Italian roads and onto a highway that cuts across the peninsula, with a tunnel right through the country's grandest mountain, Gran Sasso. At the tunnel's deepest point, with nearly a mile of bedrock resting above our heads, we'd turn off through a guarded gate and enter one of the quietest places on Earth.

We were there, in 2019, to build a particle detector more sensitive than any in history. We spent long workdays, overnight shifts and most weekends in this cavern, locked in a race with international rivals to find the missing five sixths of the universe's matter.

In spare moments while turning a wrench or staring at a pressure gauge, I'd sometimes ask my teammates what our chances were of winning that race. "Zero," they'd usually reply. Surprised, I began questioning colleagues beyond my several hundred collaborators, polling them at conferences and happy hours, and found that it wasn't just us. Few experts—among the younger generation basically no one—thought any scientific effort was on the brink of discovering dark matter.

In the seven years since, these murmurs have grown only louder. For four decades now we've failed to identify the particles that make up dark matter—the invisible chunk of the universe that we know is there, that suffuses every galaxy we see. And more physicists than ever are conceding that this situation might never change. "Nature doesn't always promise us the results we'd like," says physicist and mathematician Edward Witten, whose 1985 paper proposing that weakly interacting massive particles, or WIMPs, could be observed on Earth launched the field that I focused my Ph.D. work on. "It's unfortunate, but it's certainly possible that nature chose a dark matter particle that we won't be able to detect," Witten observes.

Many believers remain. Dark matter hunters are loping desperately in a host of directions both old and new, hoping that nature can't keep this secret forever. But I've begun to wonder where their optimism comes from and to question one of my deepest convictions: that the scientific method, given enough time and smart people, will get us over any hurdle, bringing us closer to the truth of things.

If dark matter disproves this conviction—if five sixths of all matter will continue to hide for the remainder of human history behind an impenetrable wall of unknowing—then maybe I've been wrong about science itself all along. Maybe all scientists should be grappling with a possibility they've long ignored but which many philosophers have long since accepted: That science will never give us a complete picture of reality. Or, to take this idea to its extreme—as I've begun to do in my darker moments—that our theories are merely a useful but ultimately meaningless facsimile of the world. Dark matter, I've come to believe, could thus become science's greatest lesson.

THE FIRST PROBLEM is that dark matter definitely exists. Astronomer Vera C. Rubin spent the 1970s meticulously cataloging the swirl of as many galaxies in the sky as she could. What she found was that the stars near the edge of every galaxy in the observable universe are moving way too fast. Like a racecar hitting a corner with too much speed,

these stars should be sent flying off their orbital racetracks and into the void. The gravity of everything we can see at the center of their galaxies simply isn't enough to hold them in.

Rubin's data were airtight. They left two alternatives: either gravity doesn't work the way physicists thought it did, or there's a heap of matter in every galaxy that we can't see.

The intervening decades have all but killed the former possibility. Astronomers construct gravitational "maps" of galaxy clusters based on tiny deflections of the light passing through those galaxies caused by the matter they contain. Most of this matter exists as a giant, invisible cloud superimposed on the stuff we can see with telescopes.

These dark matter maps confirm Rubin's observation: the gravity of these galaxies is about five times stronger than their visible stars and dust would suggest. And when astronomers caught two of these clumps of galaxies colliding, they found a powerful confirmation that it was matter, not gravity, that we had been wrong about.

The cataclysm, called the Bullet Cluster, stripped each clump's regular matter from its dark, superimposed cloud. The gas, stars and galaxies slowed down, roiled into a hot maelstrom. But the two ghostly halos of invisible stuff sailed right past each other, leaving their visible counterparts behind. If the solution to Rubin's mystery is a

new law of gravity rather than extra stuff, then what's in those fleeing clouds?

Joseph Howlett
is a senior reporter at
Scientific American.

XENON Collaboration (preceding page)



Two galaxy clusters collided in the Bullet Cluster, where the regular matter (pink) has been stripped away from the dark matter (blue).

The Bullet Cluster is nigh impossible to explain by modifying Isaac Newton and Albert Einstein's theories of gravity. So are other recent observations, such as galaxies with anomalously slight or severe "racecar" problems—there can be more or less missing matter in different places, but gravity has to look the same everywhere.

Even in our oldest snapshot of the universe's early contents, the so-called cosmic microwave background, dark matter's influence is unmissable. A few hundred thousand years after the big bang, "regular matter"—the 16 species of particles that make up the Standard Model of particle physics—was still a swirling soup, too hot to clump under gravity's pull. But the data reveal that dark matter was already starting to coalesce.

All this evidence led physicists to a simple, coherent, frustrating explanation. Five sixths of the universe's matter is a kind we can't see, yet it built everything we can see, and it's passing through us every moment. But what the heck is it made of?

Fortunately, the theorists had an answer ready. Their favorite theory of matter—called supersymmetry—already predicted an as yet undiscovered particle, some 50 times the mass of a proton, that

could effortlessly explain every apparent contradiction logged by Rubin and her successors. WIMPs so perfectly addressed this cosmic gap that they became known as the "WIMP miracle." And even more miraculously, we might be able to detect them.

WIMPs would interact with regular matter mainly through their collective gravitational pull. But the individual particles also had a minuscule bridge to the Standard Model: they could interact with its particles through the weak force. This meant a WIMP passing through a block of regular matter would usually whiz through like a ghost, but very rarely this ghost would become momentarily corporeal—the WIMP would collide with an atom.

In 1985 Witten and Mark Goodman proposed a simple-sounding idea: fill a tank with atoms that flash when struck, put it underground where cosmic rays can't light it up, and wait for dark matter particles to make their identity known. It seemed like the logical next step, the way things had worked throughout the 20th century, when physicists used similar detectors to pin down each of the Standard Model's characters one by one. Dark matter, physicists figured, would pan out no

differently than earlier mysteries, such as how spin works or what protons and neutrons are made of. We'd trap the mysterious entity in a laboratory and then carefully tease out its workings.

"I was giving talks, saying, 'We're going find this in 10 years,' and everybody thought that was true," says Katherine Freese, a theoretical astrophysicist at the University of Texas. Freese co-authored a 1986 paper that filled in the details of Goodman and Witten's proposal, establishing "direct" dark matter detection as a field. "We were really convinced, like, 'My God, we can do this,'" she says. "We thought it was right around the corner then."

I JOINED THE ARMS RACE near its peak, almost two decades after Freese and her cadre sparked it. New experiments were launching every year, battling to cover the full span of what the WIMP's mass and cross section (precisely how ghostly it is) could possibly be.

One technology had taken a clear lead: detectors filled with liquid xenon, pioneered by Columbia University physicist Elena Aprile. It's hard to point to a single person more responsible for our tearing through so much of the WIMP's massive parameter space so

quickly. “She really is the one who got the use of xenon going,” Freese says. So I asked Aprile to be my doctoral adviser in 2015. To me, dark matter was the biggest embarrassment in physics, and I couldn’t imagine a higher priority than using the scientific method to fix it.

The first blow to this resolve came in 2018. We had in hand an unprecedented chunk of data from the most sensitive experiment in history, XENON1T. It was poised to probe a great swath of the remaining masses and cross sections the WIMP could still have. Using fake data to blind ourselves from potential bias, we’d built up an elaborate system to automatically analyze the real thing. Now our entire collaboration had joined a conference call to press a button and watch the results unfold together. We saw our years of work collapse in seconds. I’ll never forget the sight of despair washing across a Zoom screen full of faces as our search turned up nothing.

When I went to Italy to help build that experiment’s successor, XENONnT, I started polling my peers and soon realized how little of the confidence Freese spoke of remained. That work, too, would go on to reveal nothing, as did its many competitors.

Physicists are already planning another round of experiments, based on theorists’ updated estimates of just how weakly interacting WIMPs can be. But the original miracle they pulled from their desk drawer is dead. These modified WIMPs must be tethered even more loosely to the Standard Model, by way of some additional, unknown particles.

But even if this updated guess is right, there’s a good chance we’ll never find what we’re looking for. Our bodies and underground detectors alike are constantly pummeled by billions of neutrinos produced in the sun and atmosphere. Neutrinos interact far more rarely than the original WIMP but similarly to or more often than any version of WIMPs that survived the 2010s. And their interactions are impossible to distinguish

from dark matter’s. Xenon experiments have already begun to see traces of this impenetrable “neutrino floor.”

So the community has moved on to other hypotheticals—to axions, a long-standing alternative hypothesis theorists have had ready-made since 1977, or to lower-mass WIMPs whose tiny bump wouldn’t light up a xenon atom. People are paying new attention to the possibility that dark matter is made of primordial black holes, hypothetical entities dating to the big bang that Stephen Hawking predicted in 1971. Each of these black holes swirling around the galaxy would have a mass maybe a bit less than the moon’s packed into a microscopic ball.

But what if dark matter is none of these things? What if it is not connected to our world through any force besides gravity? In that case, no conceivable technology could sense a single particle

of the stuff. Dark matter would be like a shadow realm, superimposed on but disconnected from our own except through its collective tug, its denizens utterly unknowable to us.

CALL ME NAIVE, but I never thought this could happen. The scientific method is built to encounter, interrogate and ultimately subsume any mystery it runs across. So I figured dark matter was just another speed bump. Give us enough time, and we’d figure it out like we had so many previous puzzles.

In retrospect, all those recent wins might have misled me. “Particle physics during the 20th century was incredibly successful,” says Simon Allzén, a philosopher at Stockholm University. At blackboards and colliders, my predecessors had conquered and cataloged a zoo of particles into the elegant, orderly



In 2019 the author and other physicists close the chamber that will house the XENONnT experiment at the Gran Sasso lab.

Standard Model. They came to expect a “five-sigma” standard of evidence, meaning a true discovery can have only a one-in-several-million chance of being a statistical fluke. Maybe that bar is just too high to maintain. “This has been a golden era,” Allzén says. “Modeling our scientific method on what we achieved with the Standard Model is a bad idea.”

Stop exalting physics above the other sciences—after all, as Allzén puts it, we believe in dinosaurs even though we can’t trap one in a lab—and maybe dark matter isn’t such a problem. “We have detected it,” argues Siska De Baerdemaeker, a philosopher at Stockholm University. “That you haven’t found something until you’ve found it in a lab is weirdly dismissive of gravitational detection.”

Dark matter is there. Using just its gravity, we’ve built extensive catalogs of the shadowy stuff’s presence and evolution across the eons. Maybe we should accept that the secondary goal—figuring out what its constituents are—might be beyond reach. “That would be the worst-case scenario for physics, especially for particle physics,” De Baerdemaeker says. “But nature doesn’t have to play nice.”

Still, I can’t quite shake my training. Atoms are made up of electrons and nucleons, which consist of up and down quarks. How can we call science a success if we’ll never know what this other stuff—which is almost all of the stuff—is made of?

Dark matter has me thinking I’ve been wrong about what science is even for. I thought it was the ultimate place for asking humankind’s biggest questions (How did we get here? What is everything made of? How does it all come together?) because it was the only place where you could get answers that were simply true. But are they?

Every theory we’ve ever had has technically been wrong—an imperfect approximation of reality—and we can be sure the Standard Model is no different. Dark matter is just the most glaring of its gaps, different only in degree from its other fuzzy impressions of the world, from the electron to the Higgs boson.

I’m starting to think none of these objects are any more “real” than the



The author (center) and other scientists huddle around a computer screen far below the Gran Sasso mountain, watching the results of a critical equipment test.

WIMP. They’re just theoretical ideas that help us predict what will happen, like how high school-level mechanics can predict how far away a punted football will land. I’m starting to think that is science’s actual job: predicting what will happen. The Standard Model is just a fancier version of those high school equations, a reliable framework for saying what will come out when you smash matter together at high speeds. Maybe the search for absolute truth—not just a reliably predictive picture of the world but a meaningful one—was always too ambitious.

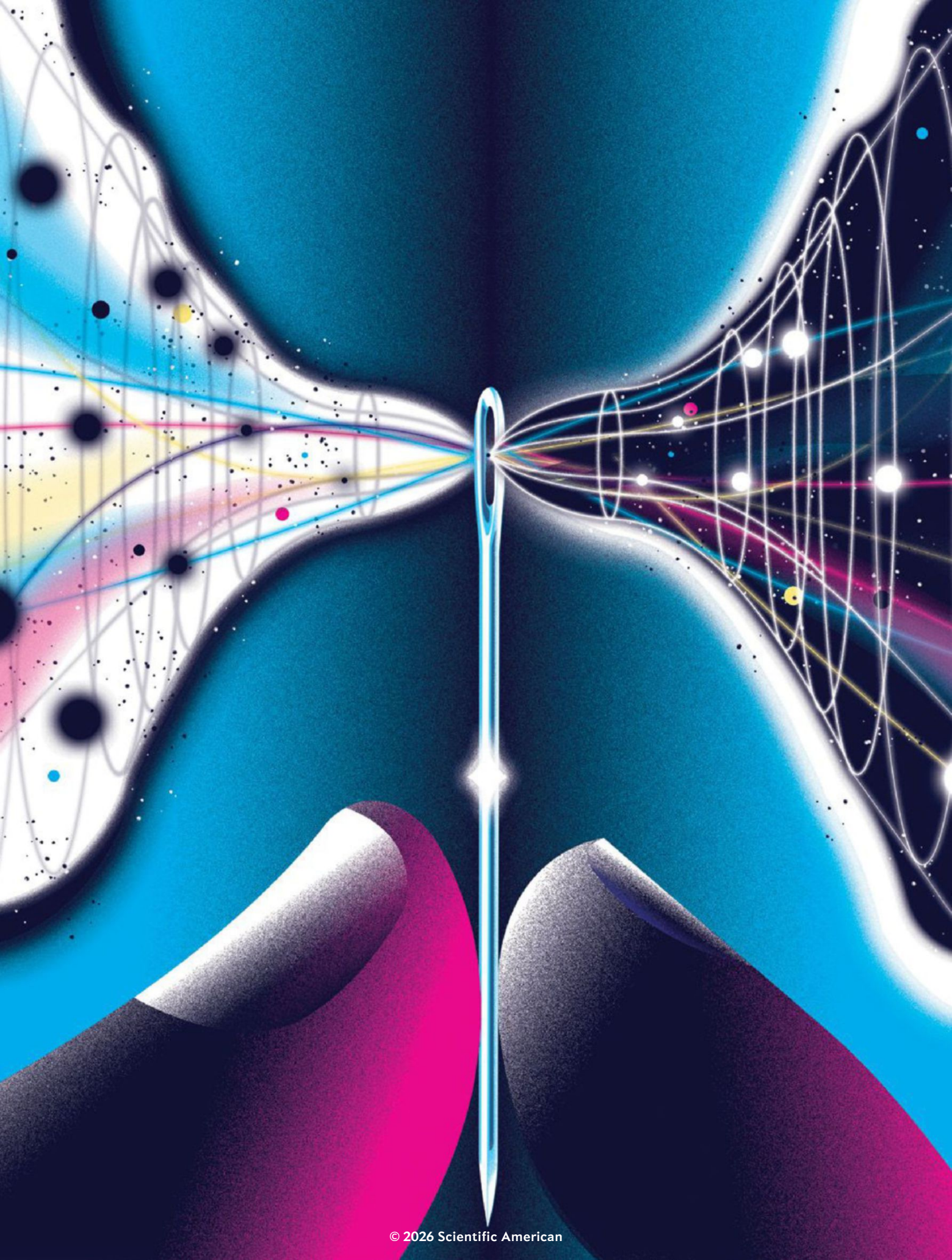
Tim Maudlin, a philosopher of science at New York University, says that I’ve retreated too far, that I should “lighten up a little.” Our theory may never be completely finished, he points out, but that doesn’t mean entities such as the electron have zero connection to reality. But Maudlin also warns against my former unassailable optimism, calling it a kind of “theological thesis.” There may be fundamental or practical limitations that stop us from ever answering a scientific question. “I mean, that’s life, buddy,” he says. “The world doesn’t care about you.”

Something like faith might be what it actually takes to be a scientist, even if it isn’t totally rational. In fact, most of the

physicists I’ve talked to still believe we’ll make sense of dark matter someday. “I do think we’ll get it,” Freese says. “Just because we haven’t solved a problem doesn’t mean the next generation won’t be smart enough to figure it out.” Aprile, my former adviser, thinks the right stroke of experimental genius is all that’s lacking. “We have to invent a tool. The progress has always only been made because Galileo invented the telescope,” she says. “Some smart kid one day will figure it out. I know it must be.”

Scientists have never really been motivated by a desire to predict where the football will land. They’re dreamers in search of answers, of meaning, whether it’s there or not, even if they have to strive toward a receding horizon. “What else is there—give up? And then what? Do something else?” Aprile asks me these questions rhetorically. Her path was never a choice. “I’m never happy, actually—that’s the problem,” she says. “Ever since I was young, I wanted to get out, I wanted to do more.”

Someone once told me that the most beautiful thing about science is how it points at its own limitations. Maybe that’s the beauty of dark matter. Maybe Aprile and the other restless dreamers have dug up the ultimate limit—one the rest of us can’t ignore. ●



PHYSICS

What Are the Smallest Pieces of the Universe?

Physicists are searching for what lies underneath the particles we know

BY JAY BENNETT

ILLUSTRATIONS BY NEIL WEBB

ON JUNE 25, 2012, PARTICLE PHYSICIST Sau Lan Wu was in Building 32 at CERN, the European particle physics laboratory near Geneva. Hundreds of feet below, the Large Hadron Collider (LHC)—the world’s biggest scientific instrument—had been conducting high-energy particle collisions for more than two years. The machine accelerates protons to near the speed of light and slams them into one another to produce sprays of fundamental particles and radiation. “Suddenly there’s a lot of noise,” Wu recalls. “We heard one of my students screaming.”

Wu had assigned one of her most capable statisticians, graduate student Haoshuang Ji, to the task of confirming whether the long-sought Higgs boson particle had briefly appeared among the collider’s showers of subatomic particles. Ji had worked through the night to combine two datasets tracking different potential signs of the Higgs.

The combined statistical significance of the datasets surpassed the threshold needed to claim a discovery. The Higgs boson was real. Celebratory cheers erupted down the corridor. “Everybody smiled more and more; our mouths became bigger and bigger,” Wu says. “This is what you call the joy of discovery.”

The Higgs boson, announced to the world nine days later, brought the number of known elementary particles in the universe to 17. It was the last particle predicted by the Standard Model, theorists’ best description of nature’s fundamental bits. The model groups particles into fermions (the building blocks of matter, such as quarks) and bosons (force-carrying particles such as photons).

These particles are the smallest bits of nature known. But can they be bro-

ken down further? “That’s what we search for in experiments,” says James Beacham, a physicist at CERN. “There’s this notion of what it means to be the smallest possible thing. Really we’re asking: What are the most fundamental ways by which the universe organizes itself? What is physical reality? It’s really a kind of profound, almost philosophical question.”

With more time and more advanced tools, scientists wonder, will we keep discovering more underlying pieces of the universe? Will we ever reach the limit—the final building block of nature? How can we truly know if we’ve drilled down as far as the subatomic layers go?

IN ADDITION TO LOOKING for smaller ingredients within known particles, physicists believe that there could be additional elementary particles that have yet to be identified. A hypothetical dark matter particle, for example, may be composed of smaller parts that we can think of as “dark quarks,” Beacham says.

The search for new fragments of reality may reveal



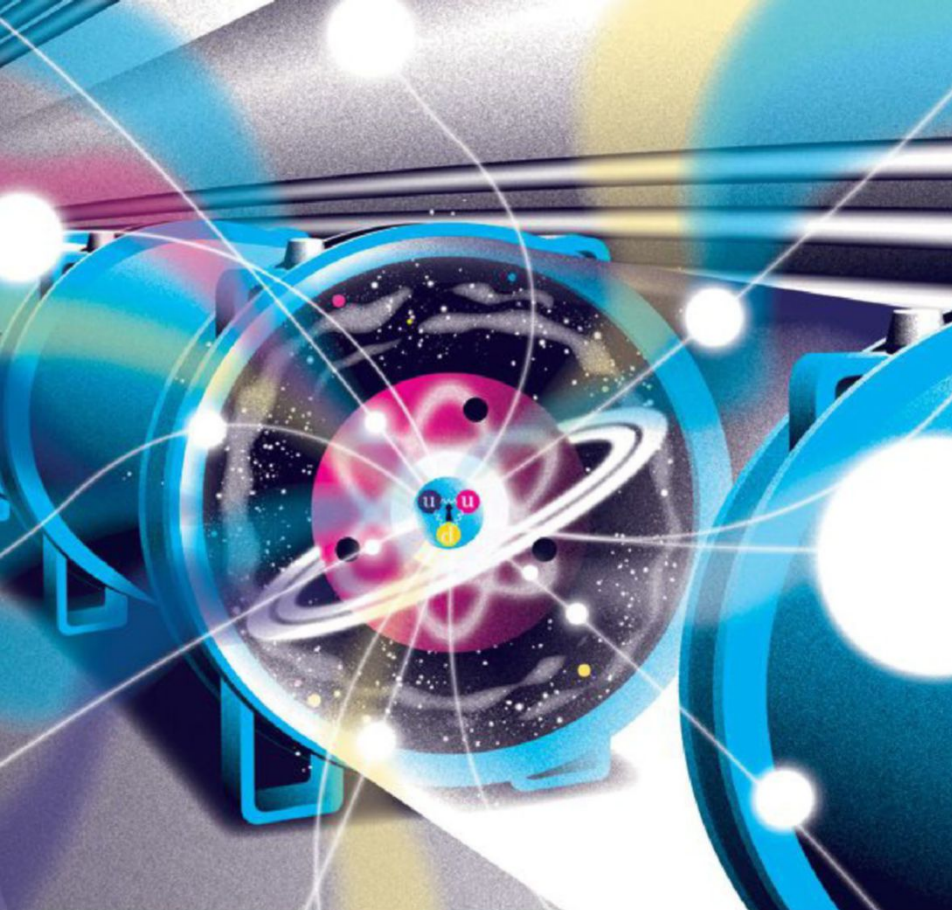
that our understanding of elementary physics is flawed. The Standard Model represents particles as points, meaning they have no volume. Scientists, however, know that they don’t literally have zero volume, but they are so small that there is no mathematical reason to include their size in physical models. (And according to the model, particles are merely “excitations” in fundamental fields that pervade the universe.)

But what if instead of points, these bits of mass and energy are actually something else, like tiny, vibrating strings? Under string theory, a particle’s characteristics would then be determined by the string’s properties and the way it mingles with other strings, all quivering and coiling near the infinitesimal limits of physical size.

“Think of strings interacting,” says Mirjam Cvetič, a theoretical physicist specializing in string theory at the University of Pennsylvania.

“Open strings can combine and split. When they combine, they can make closed strings.” Most elementary particles would be formed by open strings, she says, and closed strings would make up

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we had quantum gravity under our nose all these years without realizing.”

IF STRINGS OR QUANTUM LOOPS exist, physicists believe they would be about the size of the Planck length, which is thought to represent a physical limit to how small something can be, about 1.6×10^{-35} meter. According to quantum theory, it is impossible to measure beyond this limit because anything smaller would have physical uncertainties that would prevent it from having a definite size.

To experiment close to the Planck scale, we would need a circular particle collider centered on the sun and reaching “a little past the outer orbit of Neptune,” Beacham says. This grand space accelerator won’t be possible anytime soon, but scientists are working on upgrades at the Large Hadron Collider that are slated to come online in 2030. These modifications will allow the machine to measure even more particles erupting from collisions. The primary objective is to learn more about the Higgs boson, which may actually be multiple types of particles or could be made of composite parts.

“What are the subtle deviations of how this Higgs boson behaves?” wonders Archana Sharma, a physicist at CERN who helped to design, build and operate one of the LHC’s primary detectors. “How does it decay? How does it self-interact? Are there two bosons that can be produced or not?”

Because the Higgs has a quantum spin of zero, it is the only known elementary scalar particle. Learning more about how it behaves is crucial to understanding the ghostly medium responsible for imparting mass in the universe. “The Higgs boson could be the doorway to an entirely new physics,” Sharma says. “It’s unlike any other particle we know.”

With any luck, continuing to up the ante in the LHC could reveal new facets of reality. Whether we will ever fully understand the underpinnings of existence, however, is anyone’s bet. “Some questions may be unanswerable. That’s, of course, very, very important to accept,” Sharma says. “And we need to continue to ask nevertheless.” ●

the hypothetical particles that carry the gravitational force, called gravitons.

To accurately explain known physics, these strings must exist across at least 10 dimensions, a geometric structure that is assumed to be accessible only at tiny scales. Opening, closing and thrumming like guitar chords across layers of reality, the strings of the theory are capable of explaining the established laws of physics in literally a quadrillion different ways. To critics, this makes the theory untestable—even worthless. But to proponents, the idea has a certain kind of beauty in its ability to explain facets of the universe. That’s “not a proof,” Cvetič says, “but a compelling feature.”

AN ALTERNATIVE IDEA to string theory is the proposal that spacetime itself is made of tiny loops. Known as loop quantum gravity, this theory proposes that space isn’t smooth; instead it can be broken down into discrete bits.

Under loop quantum gravity, spacetime is a “sea of gravity that is in a tempest,” says Francesca Vidotto, a theoretical physicist at Western University in Ontario. Woven together, these fundamental loops of gravity can math-

ematically account for the curvature of spacetime.

Vidotto says this scenario is similar to being bathed in light, which is described through the electromagnetic force. “We are immersed in the electromagnetic field,” she says. “And when we try to interact at a quantum level with this electromagnetic field, the only interactions we can have are through these discrete objects, the photons.” The same relation may exist for gravity. “I think for spacetime we should have a similar intuition that we are immersed in the gravitational field,” she says. “And when we try to interact with this field at the smallest possible scale, we discover that there is this quantum spacetime, like grains.”

One tantalizing prediction of loop quantum gravity is that tiny remnants of black holes could coexist with so-called white holes—regions of spacetime that are essentially the opposite of black holes and prohibit light and matter from entering. The two could combine through quantum superposition (the ability of quantum objects to occupy multiple states at once) to form stable particles. These particles are a theoretical candidate for dark matter. “If we are right,” Vidotto says, “it’s as if



MIND

What Is Consciousness, Really?

Maybe our understanding of the concept
itself is fundamentally wrong

BY TIM BAYNE

ILLUSTRATIONS BY DTAN STUDIO





WRITE THIS FROM SANTIAGO, nestled between the snow-capped Andes to the east and the Chilean Coastal Range to the west. I am here with about 500 other consciousness researchers for our most important annual meeting. A key theme of this year's gathering is the distribution of consciousness: When does consciousness first emerge in human development? Which animals are conscious, and might it occur in artificial-intelligence systems? And can we construct a consciousness detector, something that might tell us whether, say, babies, bees or bots are members of the "consciousness club"?

These questions are among the most intractable of scientific problems. Consciousness researchers like me have been tackling them for decades. We've made some progress, yet agreement about how to tell whether an organism or machine is conscious remains elusive. Perhaps part of the problem lies with the question itself. Perhaps "consciousness" as a term doesn't really belong to the language of science.

Consciousness researchers have never agreed on what we mean when we use that word. In some disciplines, "consciousness" means "sentience"; in others, "awareness." Still others use it interchangeably with "experience" or "qualia." The muddled terminology makes it hard to tell whether the different areas of consciousness even have a common subject matter.

If appealing to synonyms doesn't work, maybe a better strategy for saying what we mean by "consciousness" is to point to clear, uncontroversial examples of it. In the same way that you might explain what "jazz" means by pointing to the music of Miles Davis or Ella Fitzgerald, so, too, might you explain what "consciousness" means by pointing to familiar experiences—feeling sand between your toes, tasting a ripe strawberry, seeing the sun reflect off a snow-capped mountain peak.

These are all states that it "feels like something" to be in. In contrast, there is nothing that it feels like to be dreamlessly asleep or deeply sedated. In the 1990s philosopher Ned Block, then at the Massachusetts Institute of Technology, introduced the term "phenomenal consciousness" to refer to this state. It's a simple concept that has played a central role in the past three decades of consciousness sci-

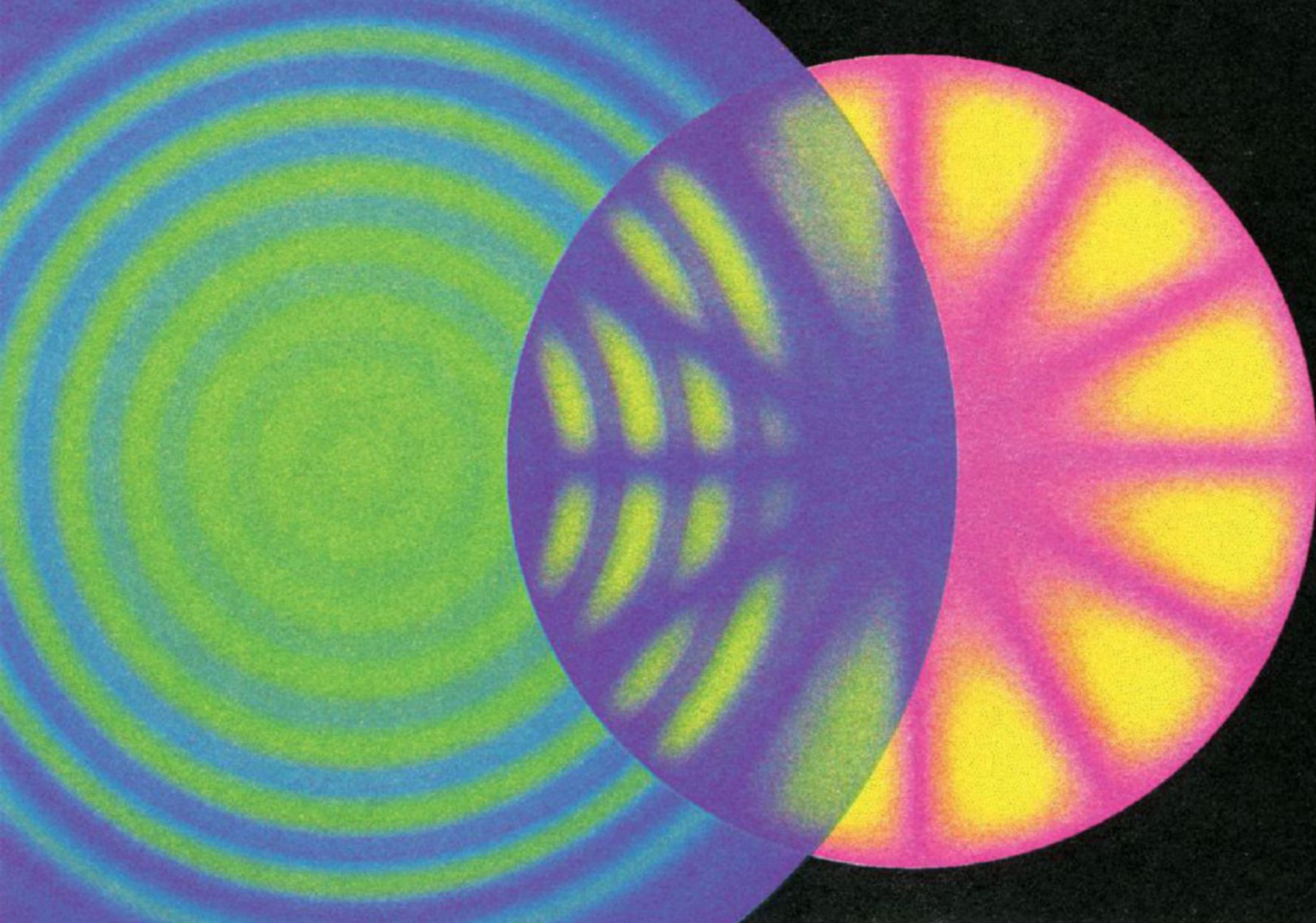
ence and guided discussions about who and what is conscious. Debates about whether it "feels like something" to be a baby, bee or bot are widely thought to carry ethical significance, marking the contrast between entities that have intrinsic moral status and those that don't.

BUT DESPITE ITS APPARENT universality, phenomenal consciousness has not always occupied center stage in how human beings have approached the mind. In fact, it is far from a universal concept. In the wonderfully named 1988 paper "Yishi, Duh, Um, and Consciousness," University of Oxford philosopher Kathleen V. Wilkes argued that there are no synonyms for "phenomenal consciousness" in ancient Greek, Mandarin, Croatian or even pre-17th-century English. (The "yishi" of Wilkes's title is perhaps the closet that Mandarin comes to a term for consciousness; "duh" and "um" are Croatian terms that have been offered as possible translations for "mind.")

Here in the Santiago region, the Indigenous language of Mapudungun addresses questions of mentality using the term "rakizum." This word captures some of what's meant by "consciousness," but it includes reflexive awareness of interdependence with other people and the natural world—relational elements that "consciousness" fails to include. One might wonder what debates about other minds might have looked like had Mapudungun, rather than English, established itself as the language of science.

The dearth of synonyms for "phenomenal consciousness" settles nothing in and of itself. (None of these languages contains synonyms for "quarks"

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or “apoptosis” either.) But it does challenge the natural assumption that understanding the space of possible minds requires appealing to the concept of consciousness. Consciousness—or at least our concept of consciousness—hasn’t always been central to discussions of the mind. Perhaps it shouldn’t be central.

SCIENCE REQUIRES CONCEPTS that support prediction, explanation and understanding. A good scientific concept is one that cuts nature “at its joints,” bundling together phenomena that share an underlying nature. The English term “consciousness” may turn out to play that role. But it’s also possible that “consciousness” will fail to make the cut—because it either bundles together phenomena that don’t really belong together or fails to bundle together things that do belong together (or both).

Precedents from this history of science are not hard to find. As philosopher Patricia Churchland once observed, the ancients grouped a wide variety of disparate phenomena together as forms of “fire”: combustion (the burning of wood); fusion (activity on the sun); electrically induced incandescence (lightning); bioluminescence (the activity of fireflies); and spectral emission (the Northern Lights). Galileo reshaped our conception of velocity by dis-

tinguishing average velocity from instantaneous velocity, and 18th-century physicist Joseph Black reshaped our understanding of heat, showing that we needed to distinguish it from temperature.

Concepts are tools. And as a tool for describing the structure of our own minds, “consciousness” is extremely useful—perhaps even indispensable. But to understand systems that are radically different from us, we may need to forge new concepts. As AI becomes increasingly sophisticated, we might find it irresistible to apply the language of consciousness to such systems, just as we are often

Consciousness hasn’t always been central to discussions of the mind. Perhaps it shouldn’t be.

tempted to use the language of consciousness in describing bees or newborn babies. But we need to recognize the limitations of consciousness talk. Certainly we should ask whether bees, babies or bots are conscious. But in asking that question, we should be alive to the possibility that the question itself might need replacing. ●



COSMOLOGY

What Came before the **BIG BANG?**

Will we ever know how the universe started?

BY SARAH SCOLES



THE BIG BANG WASN'T A BANG IN THE traditional sense, but it was the start of important things. Space, for one. Time, for another. And it began the conditions and processes that eventually resulted in us humans, who can sit here and wonder about space and time. The big bang was, effectively, the beginning of the universe. According to human logic, there must have been something before the big bang, even if “before” is the wrong word because there was no time until after.

The good news is that physicists do have ways of thinking about—and even empirically studying—the origins of the origin of the universe. Counterintuitive and impossible as it may seem, cosmologists are even making progress in determining which wild ideas might peel back the veil on that early era, even though it remains inaccessible to us.

For millennia what happened before and at the beginning of the universe was not a question scientists could even scratch at. Cosmological queries were the dominion of philosophers, says Jenann Ismael—herself a philosopher of physics at Johns Hopkins University. The most fundamental query, of course, is where we come from, a question as popular among philosophers as it is with the rest of us. Other questions, Ismael says, include doozies such as “What are space and time? Does time have a beginning? Does space have boundaries?”

Even after cosmology became a hard science, the field was a bit sketchy, Ismael says. “The science was one-and-a-half facts,” she adds. The sentiment, she says, is usually attributed to 20th-century British physicist James Jeans. But that has changed in the past century or so as the philosophers’ musings have wandered into the realm of theory, experiment and data. “These old conceptual questions are arising in ways that have new angles, a new spin and a new framework,” Ismael continues.

It’s unclear whether science as a discipline, and scientists as people, will ever be able to answer some questions definitively. After all, no one can “see” what happened before the big bang, and no one will ever be able to, at least not directly. But the current and future universe, researchers are learning, may contain clues about the distant past, ways to test theories about the before before. “I’m happy to listen to any framework, but I only start taking it seriously when it produces a clean observational target that a real instrument can go after,” says Brian Keating, a cosmologist at the University of California, San Diego. “If there isn’t a discriminant you can measure, you’re doing metaphysics with equations.”

Here are three ideas that he and other scientists take seriously about the cosmos's ultimate origins:

NO BOUNDARIES Quantum mechanics is the physics of the extremely small, ruled by statistics and uncertainty. It's also what may have shaped the early universe. To understand the quantum cosmos, scientists calculate the probability of a given output from a certain input.

In cosmology, the "output" is the universe as it looks today. "The question is: What should the input be?" says Jean-Luc Lehnert, former head of the Theoretical Cosmology group at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Germany.

Physicists can break up the problem into chunks of outputs and inputs. If they consider the modern universe to be the output, they can try to figure out what input might have produced it. Then they can step backward by taking that input as a new output and determine what conditions earlier in the universe might have produced *that* state, and so on. They can theoretically (if they have a lot of time on their hands) do that forever, going in steps to reach the before before—and even before that.

That infinite regression, however, didn't make sense to physicists Stephen Hawking and James Hartle, who worked on the question together in the 1980s. They decided to eliminate the universe's ultimate input—its "beginning." Instead they formed a model of the universe called the no-boundary proposal. They suggested that time and space form a closed, rounded surface: a four-dimensional hemisphere of spacetime.

Imagine the universe like the globe of Earth. The big bang is the North Pole. There is no "before" it, just as there is no north of north. "Before" becomes irrelevant as a concept. "It's almost like a Zen idea," Lehnert says. And it's one he's toying with in calculations to see if he can re-create the universe we see today from a round place with no north of north.

"The no-boundary proposal has a decent amount of support, or at least interest, within the physics community," says Sean Carroll, a professor of natural philosophy at Johns Hopkins. He notes that some scientists worry about how well defined the idea is, but he finds it to be a "natural starting point," given what we know about quantum gravity.

CYCLIC COSMOS Paul Steinhardt, a physicist at Princeton University, has another idea about what happened before the universe as we know it began. It stands in opposition to an idea that he helped to shape: the theory of inflation, which holds that after the big bang, spacetime expanded very quickly

for a very short period. The inflation scenario is meant to explain why the universe looks flat and similar in every place our telescopes can look.

After helping to establish inflation theory, however, Steinhardt started to doubt the idea, in part because it has required constant tweaking to keep it consistent with our measurements of the cosmos. "It's really hard to think of a historical example where that actually led to what turns out to be the right answer," Steinhardt says. "Almost always, that's a sign that the *Titanic* is sinking."

Time to get in a lifeboat, he thought. So he came up with a cyclic universe: one that balloons significantly in size, as ours seems to be doing now, then shrinks a little and then starts expanding all over again. "When people think about contracting universes, they're usually thinking about things coming to a crunch," Steinhardt says—the cosmos collapsing back down into an infinitesimally small point. That's not what Steinhardt is talking about: he thinks the universe perhaps contracts slowly, to a smaller fraction of its size but not to nothing. That shrinking smooths things out in ways that inflation fails to explain, he says, while still producing a cosmos that appears flat and the same in all directions.

Steinhardt adds that what *looks* like a big bang is actually not. The universe expands, then slowly contracts and then quickly goes back to expanding. The fast transition between contraction and expansion is not a bang but a "big bounce."

Steinhardt hopes to test this idea not just by examining the past but also by taking data from the present and watching the future carefully. "It makes an obvious prediction, which is that the current phase of accelerated expansion can't continue forever," he says. "It must end." This idea, in turn, raises a new question: "Could it already be in the process of ending now?" he asks.

Our measurements of the universe's expansion come from relatively faraway objects that emitted their light a long time ago. Things could have changed, and we might not know yet, because the effects would be hard to measure. "We'd have to look at objects very close by in order to detect" a change in the universe's expansion, Steinhardt says. That's not cosmologists' forte, and they would have to develop new techniques and instruments to look nearby for such effects.

Even more intriguingly, Steinhardt says that because "nothing bad happens to space" during the contraction and bounce, information—even objects such as black holes—can pass from before the bounce to after. "There might be things in our observable universe that are from before," he says.



MIRROR UNIVERSE Latham Boyle, a researcher at the Higgs Center for Theoretical Physics at the University of Edinburgh, who was formerly Steinhardt's graduate student, has another big idea about the before before. Like the big bounce concept, Boyle's favored proposal is pretty simple conceptually, and it also avoids inflation. "There's the universe after the big bang and the universe before the big bang," he says, "and they're kind of mirror copies of each other."

Picture this, Boyle says, like the points of two ice cream cones touching each other, with their contact representing the big bang. "Time marches away from the big bang in both directions," he says. On our side, it goes forward; on the mirror side, it goes backward. What happened before the big bang is the reflected opposite of what happened after. And that doesn't just include time: here there is matter; there there is antimatter. Here left is left; there left is right.

Boyle has ideas for observations that could support (or nullify) his theory, which is called the CPT-symmetric (charge-parity-time-symmetric) universe. For one, a CPT-symmetric universe wouldn't have sent gravitational waves shimmering through space from the beginning of the universe, as classical cosmology theories predict. Astronomers have been hunting for such signals. If these waves are eventually detected, that would rule this idea out.

Boyle's hypothesis also predicts that dark matter could be explained by a particular kind of neutrino. He hopes cosmological instruments will reveal more information about neutrinos soon. The model's connection to particle physics, among other aspects, makes this idea intriguing, Carroll says. "What I like here is the economy," Keating says, "and that it sticks its neck out," focusing on the kinds of specific, physical predictions experimentalists like him need.

EACH OF THESE SCIENTISTS is attached to their own idea. But Lehnert isn't confident any of them will stand the test of time—whatever time is. "I think it's completely preposterous that, in the year 2025, we should understand the beginning of the universe," he says. In the grand scheme of things, in other words, we're still at the beginning of our journey of understanding. "Why not in the year 2,000,025 or whatever?"

And even if researchers think they are getting close, they could be approaching a false summit: that frustrating place that looks, when you're hiking, like the top of the mountain but is actually a mere bump blocking your view of the true peak. "In general, I think it's extremely plausible that there was something before the big bang," Carroll says, "but it's also very plausible that the big bang was truly the beginning. There's too much we're just unsure about, and I am a bit skeptical that the state of the art is good enough to allow us to draw any firm experimental or observational conclusions out of any of these models."

But cosmologists aren't studying our ultimate origins because they think the mystery will be resolved in their lifetime. Lehnert imagines himself as part of an intergenerational project helping humanity trek closer and closer to a truth we may never find. It's almost as if the mystery isn't within the realm of science. But science often involves probing things we can't access, at least at the start, Ismael says. Scientists predicted atoms before we could see them, and black holes and dark matter still lie beyond our ability to detect them directly. "I think the benchmark for what counts as science has moved," she says. And it will continue to—including, perhaps, backward to the before that may not be a before. ●



A centuries-old apple tree on Verona Island in Maine became the subject of a years-long detective story.



AGRICULTURE

The Mystery Tree

Breeders, professors and enthusiasts wanted to identify an old orchard relic. They ended up rewriting the history of American apples

**BY MARYN MCKENNA
PHOTOGRAPHS BY GRANT DELIN**

IT WAS A ROUTINE DAY IN THE LABORATORY BELONGING TO Cameron Peace on the campus of Washington State University, Pullman, in the high, dry hills close to the Idaho border. Peace is a tree-fruit geneticist, and on this warm September afternoon, as on most days, he was running programs that tease out the DNA profiles of apples. Apples are Peace's passion and the focus of his professional expertise. He maintains a backyard collection of unusual varieties and runs a project called MyFruitTree, which lets members of the public send in leaves from unidentified apple trees and matches those trees' genetic fingerprints to entries in a database of known types.

Washington State University is a land-grant university, founded to research and support agriculture, and Peace was honoring that mission. The samples he was examining had come from a team on the other side of the country at the Maine Organic Farmers and Gardeners Association (MOFGA), a long-standing agricultural nonprofit. The group wanted to identify trees it had found on old and abandoned farms, hoping to salvage valuable rarities before high winds or harsh winters killed them.

Peace does this work because every analysis he runs benefits his central project, a literal family tree of North American apples that traces the distribution of distinctive traits—flavor, color, hardiness, disease resistance—through siblings, parents and forebears. He plugged the data from a Maine sample coded AMHO-504 into a spreadsheet tool that would compare it against his collection. Then he sat back, agape. High up in the continental pedigree the entire DNA fingerprint matched a predicted empty space. The Maine team had found a living lost progenitor to hundreds of varieties—a tree that had been contributing its characteristics to American apples for hundreds of years.

That afternoon three years ago was the culmination of a detective story that spanned continents, collapsed centuries and linked the unlikely collaborators. Two quests drove their efforts. They wanted to identify a mystery tree on a property that dates back to the American Revolutionary War. But they also wanted to uncover what the possibly oldest living apple tree in the U.S. contributed to generations of apple varieties—and, equally, what traits it might still harbor that could

be bred back into apples today to protect them against new threats in the future. “Maybe there are aspects that people didn’t value in the past and, 200, 300 years ago, selected against,” Peace says. “But these days, actually, we do need them.”

SCIENTISTS SUCH AS PEACE, AND DETECTIVES such as the team that brought the mystery apple to him, agree that retrieving those genetic resources is a vital task. For one thing, apples are valuable. They are the fruit Americans eat the most and one of the top commercial crops in the U.S., which grows more apples than any other country outside China. Apple harvests are rising in volume all the time, but in genetic terms, the base of that towering, crunchy mountain is narrowing. Although about 2,500 varieties exist in the U.S. and roughly 100 are raised commercially, most of the market depends on just 15 of them.

And apples are under threat. When small numbers of varieties are planted very widely, the crop becomes more vulnerable to diseases such as fire blight, powdery mildew and scab. Having near-monocultures in the field means disease organisms don’t have to rely on the evolution of new mechanisms to overcome the diverse genetic protections collectively carried by many apple varieties; once they settle genetically on a strategy, they can attack. And they do, very successfully. A U.S.-wide estimate made more than 20 years ago put the annual cost of fire blight, a bacterial disease, in excess of \$100 million. Since then, outbreaks in various parts of the country have cost producers \$16 million to \$42 million at a time.

Maryn McKenna

is a journalist specializing in public health, global health and food policy and is a contributing editor at *Scientific American*. She is author of *Big Chicken: The Incredible Story of How Antibiotics Created Modern Agriculture and Changed the Way the World Eats* (National Geographic Books, 2017).

Changing weather patterns are compounding these effects by creating conditions that encourage the growth of bacteria and fungi or by pulling the seasons out of sync with apples' growing patterns, forcing trees to bud earlier and making flowers and fruit more vulnerable to temperature shifts. Washington State, the leading apple producer in the country, lost more than 2 percent of its crop to a heat wave in 2021.

Given these realities, retrieving genetics that have been lost to time and market contraction is crucial to apples' survival. Worldwide, scientists are working to associate specific DNA segments with qualities that apples will need under future conditions so that those traits can be bred back into the fruit; the genetic markers can then be used to confirm that the breeding was a success. They are also looking for places where gene variants from long-surviving varieties have been retained in trees growing today; that persistence demonstrates how genetically useful those qualities have been.

Scientists carry out that work on apples grown by commercial breeders and held in agricultural-school collections—but they also rely on apple enthusiasts who bring them fruit for which names and provenance are unknown. Of course, those amateur detectives aren't hunting rare varieties primarily to serve science. They are looking for lost trees for the charm of their names, the complexity of their histories and the love of apples themselves.

All these motivations were present in the self-assembled team—a historian, several apple hunters, two dedicated homeowners, and a crew of geneticists and breeders—that brought the Maine tree to Peace's attention and hunted across continents and back through centuries to retrieve the lost apple's name.

JOHN BUNKER WAS BARELY INTO HIS 20S WHEN he realized apples might end up being his life's work. During a preteen summer visit, he imprinted on Maine like a duckling on a zookeeper, vowing to

Apple varieties on display at the Maine Organic Farmers and Gardeners Association Common Ground Country Fair





Apple detective John Bunker in his orchard

get back to the state when he was old enough to chart his own path. He managed it by attending Colby College, a small school with a tradition of environmental programs. It was the early 1970s and the peak of the back-to-the-land movement. Bunker and some of his friends started driving around the middle of the state, looking for cheap property. They found a plot—more than 100 acres—in the tiny town of Palermo. “It was inexpensive, and I was young and wanted to live in the woods, and it seemed like the right thing,” Bunker says.

There were old apple trees nearby. Bunker remembers his first reaction was, “Free food!” (and maybe booze, too; he had tried making cider at Colby). But after a few years of homesteading, he became curious to know more. He started knock-



ing on doors, asking about past owners and what they grew—and, increasingly, about apples, which became more fascinating to him the more he learned.

A quick pause for biology. Apples don’t self-pollinate the way that tomatoes and peppers do, fertilizing and germinating with no outside assistance. Instead they cross-pollinate: pollen from one tree travels to a blossom on a second, thanks to a helpful bee that carries it. This means each fruit has two parents, just like humans do—and, also as with humans, the parents don’t get reproduced identically. Instead their offspring possess unpredictable combinations of traits—which, just as in humans, often aren’t fully identifiable until some number of years pass. So if you want to precisely reproduce an apple variety you like, you don’t start it from a seed. You clone it by grafting, which means cutting a short piece of twig, inserting it into the trunk or branch of a different “rootstock” tree and letting it grow up. Generations of grafting can carry an apple variety unchanged into the future, and because trees are long-lived, grafted apple trees can survive after the people who valued and named them have died or moved away.

As Bunker learned about Maine apples, he began to understand how fragile that knowledge was, dependent on what people remembered about texture and taste and best use. He took on the task of saving it, talking to old-timers, studying neglected trees on old farm properties, and hauling

fruit home to examine and document. “I had no knowledge at all,” Bunker says now, 50 years after he started. “At a certain point after I exhausted all the information that was out there, I realized I was going to have to develop a system for identifying things. Because I was getting into the ones that were more obscure, the local historic apples.”

Over decades Bunker became the expert he had needed, teaching himself to classify apples by characteristics such as color, stem depth, bark appearance, and the pattern of seed cells in fruit sliced horizontally. He founded a fruit-tree nursery named Fedco Trees and sold grafted descendants of trees to ensure their ongoing survival and give himself an income while he kept apple hunting. And by excavating the history of abandoned apples, he created enthusiasm and demand for them.

When Bunker staged apple-identification events at agricultural fairs, people lined up to talk to him, clutching apples from family properties, and others asked him to come give talks. One of the latter was Jeanne Russell, who lives with her husband, Ron, on Verona Island, a narrow sliver of land where the Penobscot River begins to open to the Atlantic. In 2007 she invited Bunker to a gathering of the Bucksport, Me., garden club. It took place at the Russells’ property, where they have lived since 1979; they have traced its past ownership in local records as far back as George Washington’s first secretary of war. On its long sweep of lawn, which hangs above a river channel and below pines that house Bald Eagles, there are about two dozen apple trees, and some of them looked ancient.

After his talk, Bunker strolled the property with the Russells. There were towering crabapples and thick-trunked trees that looked robust enough to bear fruit for years to come, as well as some tottering old specimens leaning sideways and barely hanging on to life. Bunker sketched a rough map on the back of the manila folder he had carried his notes in and marked the ones he thought he recognized: Ben Davis, Yellow Bellflower, Tolman Sweet. At one edge of the lawn, he recorded tree number 26 as “unknown”—a notable notation from someone as knowledgeable as him.

Later, Bunker would tuck the map away, promising himself to go back. In fact, he wouldn’t return to the Russells’ farm for many years.

FARTHER EAST FROM THE RUSSELLS, in the tourist town of Bar Harbor, a historian was exploring a different question: where Maine apples came from. Todd Little-Siebold is a professor at the College of the Atlantic, a tiny school—it has 350 students and 33 faculty—that focuses on



human ecology and hands-on learning. He landed there as a new Ph.D. specializing in colonial and 19th-century Guatemala and looked around for a project that would layer his knowledge of agriculture and economics onto the New England landscape. He settled on apples.

Little-Siebold began taking his students to properties where old trees could make history visible for them. “I introduce them to trees so that they ask the question, Who planted this tree? How could we find out?” he says. “There are agricultural census records and deeds and all these different ways that we can reconstruct what was probably grown here and who grew it.”

Trying to identify the apples on old homesteads was a natural next step. With his students, Little-Siebold started delving into nursery catalogs from previous centuries, along with diary accounts and monographs filed away by historical societies. It was satisfying work because it opened up the history of that part of Maine, which doesn’t share the

There are about 2,500 varieties of apples in the U.S.

English, Pilgrim heritage of southern New England. Much of Maine was once part of the New France of eastern Canada, a key transit point for fish and fur from the 1500s until Great Britain seized control in 1763. Little-Siebold could perceive the remains of that footprint in the apples his students were sleuthing: they were historic French varieties, not English, with names such as Calville Rouge and Reinette Franche. He started to develop a theory of French apples as an unknown backbone of early American agriculture, living evidence of the complex patterns of European settlement.

Maine is large but has a small population, so it was inevitable that Little-Siebold would meet other old-apple enthusiasts—not only Bunker but also Russell Libby and Laura Sieger, then the director and orchardist, respectively, at MOFGA. That group had spent years preserving knowledge useful to small-scale and organic farms and had turned to protecting farm products as well. With Bunker's guidance, it established the Maine Heritage Orchard in 2012, seeking to regrow trees found in the state and to perpetuate them by offering scionwood—the twigs that become grafts—to farmers, collectors and historians. After meeting members at a 2018 conference,

Peace joined the loose coalition. He offered the use of his DNA-fingerprinting techniques to identify the orchard's more than 300 apple trees.

It was an extraordinary gift. Across centuries, apple growers had written down their personal observations of blossom tint and twig width and skin color but lacked tools for objective confirmation, such as photographs or Pantone codes. The apple hunters understood that the reidentification of a fruit based on an old name risked being an interpretation of an interpretation. DNA analysis could banish that uncertainty—if an apple had been analyzed before. “This supercharged this work,” Little-Siebold says. “The DNA has answers that no archive has, where no diary survives, no journal survives, none of the stuff that I normally work with exists. There's a genetic archive that will tell us what an apple is.”

The detectives redoubled their searches. At some point Bunker remembered his visit to the Russells' property and the map he had drawn; he reminded Little-Siebold of the trees, and the professor volunteered some of his students for a new trip. Escorted by Sieger and by Peter and Kathleen Jenkins, apple enthusiasts who lived in a nearby town, the group found No. 26 at the edge of the lawn. It

Ron and Jeanne Russell stand in their garden with the 300-year-old mystery tree.



was gnarled and tilted sideways, and its trunk was almost hollow, a void surrounded by bark—but it was still bearing chartreuse-yellow apples overlaid with the rusty webbing known as russetting. They collected the sample Peace needed: a few leaves just budding at the end of a branch. They slid them into a sample tube Peace had sent, capped it and sent it off to Washington State.

At the university, Peace labeled the sample AMHO—to indicate an apple from the Maine Heritage Orchard—504. He held it in his lab until he had accumulated a big enough batch to justify delivery to the commercial lab that performs genotyping for him. In June 2023 he sent the leaves off. That September he received the results and plugged them into his database.

The Russells' toppling little tree wasn't just any unknown apple: it was a grandmother, a hypothesized unknown founder of multiple American varieties. Segments of its genetic traits were evident in apples now found throughout the country, the way an eyebrow shape or an eye color might recur across generations of a family. But the apple itself had no match anywhere in the database Peace had been building. The Russells' tree was its first discovery in North America.

Peace couldn't tell them—not yet, anyway—that he already knew its name.

THE QUEST TO PARSE APPLES GENETICALLY is an international pursuit because the knowledge the fruits contain is crucial to preserving such an economically important crop. Thus, apple detectives are distributed internationally as well. One of them is Nick Howard, a molecular geneticist who earned a Ph.D. at the University of Minnesota, home of the incredibly popular Honeycrisp. Howard collaborated with Peace and then continued the relationship when he moved to Europe to do a postdoc. He landed as an apple breeder in the Netherlands, one of the leading apple-exporting nations, performing a combination of academic research and practical application.

Howard, Peace, and some other scientists around the globe share the same method for fingerprinting apple varieties: they document each tree's unique array of single-nucleotide polymorphisms, or SNPs (pronounced "snips"). At these genome locations, a pair of nucleotides, the rungs in the twisting ladder of DNA, includes a substitution that shows up like a spelling error. Using tiered tests—48 SNPs in a first round, thousands in a second—researchers can determine whether a tree has already been identified and then explore its details if it is unique. Peace uses the results to



Tree DNA samples
prepped for analysis

reassemble the genetic history of American apples. Howard's goal was to document characteristics and connections across the world.

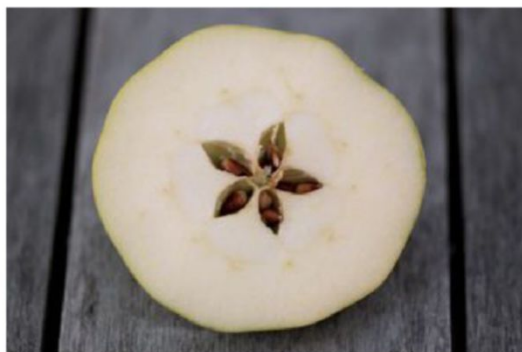
This work is not done just for archival purposes. "Genetic analysis opens up a new toolbox for the breeder," Howard says. Studies are constantly associating genome segments with specific qualities: acidity, sweetness, texture, color, aroma, resistance to disease. Using such markers, geneticist breeders can select trees that harbor desirable qualities and then set up crosses, planning for the offspring to gain benefits without losing what made the parents worth growing. This approach isn't genetic engineering, which would entail snipping DNA from a promising apple and inserting it into something that needed improvement. Instead it is the old-fashioned, unpredictable process of pollinating and growing, made more precise by genetic information. "Once you have your seedlings, you can take a leaf sample and look at the genetics and see, Does this have the disease resistance I wanted in this cross?" Howard explains. "If yes, you keep it. If no, throw it out."

The tree was a grandmother, a hypothesized unknown founder of multiple American varieties.

Howard's survey of apples' relatedness didn't only show him how characteristics had moved through the cultivated varieties across generations. It also demonstrated places where intervening generations carrying those characteristics ought to exist. Using analytical techniques that already existed in the industry, he was able to infer what those parent and grandparent apples would look like genetically if they were ever recovered. He called them "unknown founders."



Drap d'Or cuttings grafted onto another variety of apple tree



Parts of Howard's giant database have never been published anywhere because they contain SNP data that have been shared with him privately. People brought data to him because they wanted to know whether trees in university or personal collections had correct names and accurate histories or were misidentified duplicates that could be sacrificed to free up orchard space. He could draw conclusions from the shared data, but he wasn't free to publish them until the owners agreed.

One collaborator, Bjarne Larsen, had given Howard access to a trove of apple genotypes from Denmark, the fingerprints of an orchard of historic cultivars maintained at the University of Copenhagen. Larsen had done his Ph.D. in plant breeding there, had written a book on old apple varieties and then had moved for a postdoc to the same Dutch university where Howard had settled. Because he had researched them for his book, Larsen could link the genetic proofs of apples' identities to the historic evidence—where they had been grown, what they were good for, who had written about them.

One tree in the University of Copenhagen's collection had an especially interesting story. Larsen believed it was a variety named and described in a French pomological text in 1628. A later account said it was so prized in French farming that trees had been hidden in a botanical garden to protect them when the French Revolution ravaged aristocratic estates. It had once been widely cultivated in Germany and Denmark but had fallen out of favor. It was called *Drap d'Or de Bretagne*—"Brittany's cloth of gold."

When Howard added Larsen's Danish data to his database, the *Drap d'Or*'s entry shone out. It matched his Unknown Founder 13. When the MOFGA sample matched it two years later, Howard and Peace understood immediately what the Maine mystery tree meant: a lost piece of apples' history, grown in only one location in Europe, had suddenly been discovered in North America—the only known one on that continent, too. And because the Maine tree was an exact match, it could not have been a wild seedling accident. It represented a tree that someone had grafted and nurtured and carried into a new world. "It really tells you something about how people appreciated that cultivar historically," Larsen says. "If immigrants brought that cultivar with them across the Atlantic and planted it in their gardens, it's because it really had a value for them."

THE CONVENTIONS GOVERNING WHO OWNS plant genetic data and who is entitled to disclose them—even if they have been submitted to a shared international database—are com-

plex. They led to Howard, Larsen and Peace all being able to acknowledge among themselves that the name *Drap d'Or de Bretagne*, the University of Copenhagen's tree, the characteristics expected in Unknown Founder 13, and the genotype data retrieved from Maine all added up to the same thing. But the rules also kept them from immediately announcing the name to the civilian apple detectives. That had to wait for almost another year, until publication of a scientific paper in August 2024 in which Howard and Larsen shared authorship with scientists from four other countries. One of the paper's supplements associated the name *Drap d'Or* with the Danish genotype. With that information public, Peace felt free to take the next step.

The lost apple was just one among almost 1,000 in that paper's spreadsheet. Yet to the Mainers, the announcement was momentous. For the Russells, learning their apple's history validates their stewardship of a place they have invested almost 50 years in preserving. Bunker, who has probably rescued dozens of apple varieties, although he long ago lost count, says it represents "the importance of connecting with plants and with history and place." For Little-Siebold, it means vindication for a chapter of history usually excluded from the American story—but also reinforcement for the way genetic detection can carry forward the work that apple hunters put in.

For the geneticists, though, the identification of the *Drap d'Or* isn't only about illuminating the past. It also represents the promise that the apple's characteristics, only partially preserved in its many descendants but now recovered intact, may improve fruit yet to come. "Thousands of cultivars were grown in the past, and only a small fraction of those are represented in the surviving trees that are out there," Peace says. "The fact that they've survived through so much neglect, so many extra freezing winters and drought and all sorts of stuff over the decades—obviously they've got some resilience genetics in them. We should be tapping that as much as possible, understanding it, and incorporating that into development of new cultivars."

That work may soon be enhanced. It turns out the Russells' tree isn't the only *Drap d'Or de Bretagne* in the U.S. On September 21 of last year, a nonprofit housing counselor named Hannah Tays dashed up to a table in a tent at the Common Ground Country Fair, the hugely popular agricultural festival that MOFGA stages every year on its expansive grounds. It was a Sunday evening, the last hour of the fair's last day, and Bunker and Little-Siebold were preparing to pack up the apple-ID table they had been running all weekend.

Tays unrolled a brown paper bag and pulled out fruit from a scraggly, bifurcated tree that stands at the end of her property in Belfast, Me. The apple was yellow-green and fretted with russetting. Little-Siebold looked at it, looked at Bunker, looked back at Tays. "This is the apple we've been waiting for all weekend," he said.

A few days later Bunker visited Tays's tree to gather leaves for analysis. When the Maine team sent that sample for processing, it included some extras: leaves plucked from a roadside tree that Peter Jenkins had spotted in the town of Prospect. That tree's owner said it had been grown from a graft of a family tree planted during the Civil War. One day this past April, Peace woke early, found an unexpected e-mail from the genotyping company and hurriedly downloaded the raw data. A few hours later he sent Bunker and Little-Siebold two e-mails bearing smiley faces: Both trees were identical to the Russells' tree. They were all *Drap d'Or de Bretagne*.

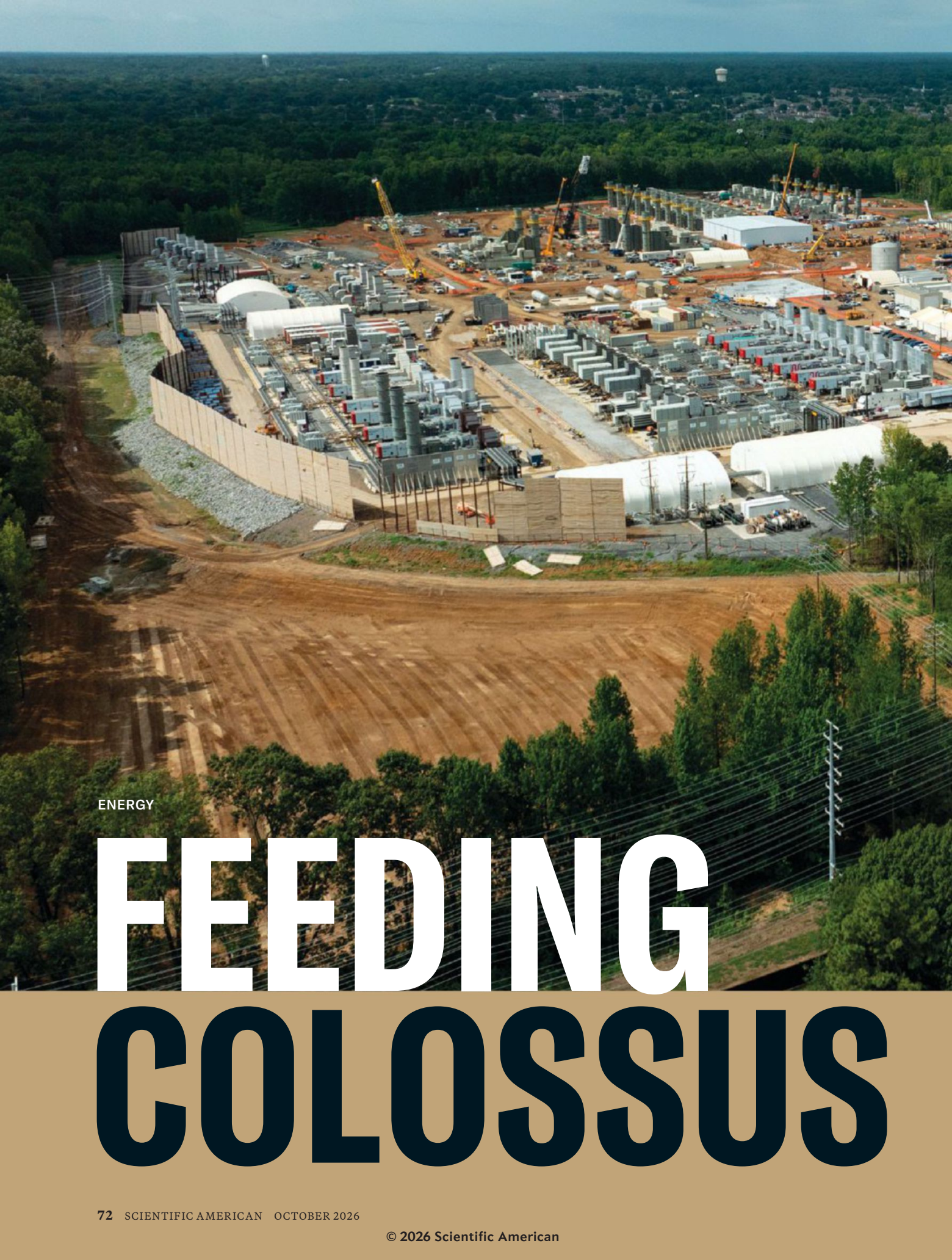
Maybe the team should not have been surprised; the three locations lie within 20 miles of

A lost piece of apples' history had suddenly been discovered in North America.

one another, and that entire area in Maine was settled early by the French colonists Little-Siebold has researched. The findings showed that the original identification hadn't been a mistake scientifically or a mistaken assumption historically. That there were several additional trees demonstrated that early colonists had valued the *Drap d'Or*, shared it and grown it in different landscapes—fields and river cliffs and uplands—and that the trees had thrived and persisted and still remained.

"It helps to fill out the story of what happened," Peace says. "The other thing it verifies for us is that we need to just keep testing lots more trees."

This is not just true of Maine. Across the U.S., there may be hundreds of spots where early colonists and their Indigenous allies planted trees they loved—and then, over centuries, we forgot their origins, their uses and even their names. Already, in other fruit-growing areas, there are other researchers and enthusiasts looking for lost apples, hoping to recover their genetic resources and reassemble their histories. Somewhere there is another tree that harbors a piece of the American past or a protection for apples' future. We cannot know, until we look, what treasures remain to be found. ●



ENERGY

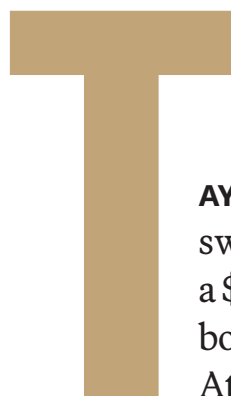
FEEDING COLOSSUS



SpaceX's Southaven power plant feeds one of its data centers across the Tennessee state line in Memphis. By July, Mississippi regulators counted 69 temporary gas turbines at the site—more than double the number the company had previously acknowledged.

To fuel its AI data centers, Elon Musk's SpaceX has assembled a private power system across two states, ahead of permanent permits and next door to people living with the noise and exhaust

**BY AUSTYN GAFFNEY
PHOTOGRAPHS BY KEVIN WURM**



TAYLOR LOGSDON WAS 20 WHEN SHE AND HER HIGH SCHOOL sweetheart moved up their wedding so she could buy a \$79,000 house in Colonial Hills, a mixed-income neighborhood of winding, tree-lined streets in Southaven, Miss. At the time, state law would not let her do so alone before she turned 21; she was told marriage would make it possible. About 11 years later that house sits near what could become one of the largest power plants in the state, a thicket of gas turbines assembled to feed SpaceXAI's artificial-intelligence ambitions.

Beyond Logsdon's neighborhood, the power plant is mostly hidden. Along the road, black privacy fabric wraps the tall chain-link fence surrounding the Southaven site. Past a thin line of trees, metal stacks rise above the fence, and exhaust shimmers in the heat. A \$7-million sound wall does little to muffle the noise, which drills through the walls of nearby homes: a constant drone like a plane taking off and never leaving.

The turbines are there because SpaceXAI needs an enormous amount of electricity for Colossus 2, one of the country's densest concentrations of computing power, where the company is training Grok, its chatbot. The data center sits just north of the Tennessee state line, in Memphis's Whitehaven neighborhood; the main power site sits across the border, in Southaven. The gas burns in Mississippi; the electricity crosses to Tennessee. The grid couldn't deliver enough electricity on SpaceXAI's timeline, so the company brought generation onsite with portable gas turbines rather than waiting for a conventional power plant or utility upgrade. The turbines were installed under Mississippi's determination that portable equipment could run for up to a year without air permits. In April the NAACP sued, calling the operation an unpermitted power plant—a fleet that state records later showed had grown to dozens of machines. By July the plant had a capacity of about 1,775 megawatts, rivaling the state's largest power plants—enough to electrify more than 1.4 million homes or a city more than 60 times Southaven's size.

Across the country, AI companies are building hyperscale data centers, and power has become the constraint. Data centers now use around 4 to 5 percent of U.S. electricity, and the Electric Power Research Institute projects that share could reach 9 to 17 percent by 2030. "Companies are making a decision that it's in their best interest to go as fast as

possible because every day that they're not online, they would be losing potential revenue," says Costa Samaras, an engineering professor and director of the Scott Institute for Energy Innovation at Carnegie Mellon University. Cleanview, an energy-data firm tracking the industry, estimates that AI data centers can generate \$10 million to \$12 million in annual revenue per megawatt. Bringing a large facility online even a few years early can mean tens of billions of additional dollars.

By June the Southaven dispute had expanded far beyond the city. Elon Musk's SpaceX, which acquired xAI earlier this year and folded it into an AI arm called SpaceXAI, raised \$75 billion in an initial public offering, pushing Musk's estimated net worth briefly above \$1 trillion. A few days later the Department of Justice moved to intervene on xAI's side and asked the court to dismiss the NAACP suit, arguing that shutting down the power source for Colossus 2 would threaten AI innovation and national security. In a sworn declaration, the Pentagon's chief digital and artificial-intelligence officer told the court that Grok is one of only four proprietary frontier AI models currently capable of supporting national-security applications. The Pentagon was also a customer: the previous summer it had awarded xAI a contract worth up to \$200 million, and the company launched Grok for Government the same day.

In Colonial Hills, the stakes are measured more simply: by who gets the power and who breathes the exhaust.

I MET LOGSDON IN HER DRIVEWAY, where she sat in a deck chair as the brass bell of an ice cream truck occasionally cut through the plant's drone. Her husband earns \$21 an hour as a landscaper. Their mortgage is about \$500 a month. She doesn't believe they could afford to move.

Austyn Gaffney is a climate and energy writer based in Louisville, Ky. She has written for *The Atlantic*, *National Geographic* and *The New York Times*.

The noise is especially hard on the couple's kids, all 12 or under, who say it keeps them up at night. Before the turbines arrived, their son, Dallas, was obsessed with xAI's founder. "We actually were kind of Elon fans," Logsdon told me. Dallas received a weekly science magazine that featured Musk, and he told his mom he wanted to grow up to be like him. "Elon probably doesn't know [this plant] was built between two neighborhoods," she said, "he's so high up."

Low-frequency noise from the Southaven turbine plant could be four to 16 times as loud as the background noise typical of a quiet suburban neighborhood, depending on the distance from the plant, according to a [March report](#) by acoustics firm Roland, Woolworth & Associates. The noise has drawn [its own lawsuit](#): residents, including Logsdon, filed a class action alleging lost sleep and falling property values.

Logsdon said she is not anti-AI or anti-Musk, but she helped to form the [Southaven Safe and Sound Coalition](#) to advocate for her community, especially over the less visible effects of air emissions. She installed three air monitors—two outside her front door and a third atop her camper, the Four Winds Express—to learn what her kids and older neighbors might be breathing. A preliminary [analysis of readings](#) taken over four months found that fine-particulate-matter (PM2.5) concentrations around her house exceeded the Environmental Protection Agency's daily health-protection standard about a third of the time. (The monitors could not determine how much of the pollution came from the power plant.) At least 10 schools, three daycares, two libraries, 11 parks and 27 churches sit within two miles of the plant, according to the coalition.

Dozens of gas turbines in one place can produce very high levels of nitrogen oxides, according to Daniel Cohan, a professor of civil and environmental engineering at Rice University. Those pollutants can irritate the lungs, worsen asthma, and form ground-level ozone, the main ingredient in smog, which builds quickly in the heat of a Mid-South summer.

The NAACP's lawsuit hinges on whether scores of portable machines operating together constitute a single stationary source, which the plaintiffs argue should trigger the Clean Air Act's permitting requirements. The Mississippi Department of Environmental Quality, or MDEQ, allowed xAI to operate the turbines without air permits so long as each was removed within 12 months. xAI later received a permit for 41 permanent turbines at the same site, with a total capacity of around 1,200 megawatts. The state's public hearing on that permit drew more than 300 people, and every speaker opposed it. According to local news reports, no one from the per-

mit board attended, and no one from xAI spoke. At least 27 of those permanent turbines were under construction as of July, according to MDEQ.

In January the EPA said [temporary turbines](#) that exceed federal emissions thresholds may still require permits. MDEQ had said it would evaluate enforcement if a portable unit remained after the 12-month deadline. On July 30, just before the first units were due to reach that limit, a Mississippi commission acting through MDEQ signed an agreement with xAI affiliate MZX Tech, the SpaceX subsidiary that owns the site, allowing 13 turbines to keep operating through the end of the year, citing delays in construction of the permanent plant. The agreement also set a rolling timetable for the rest of the temporary fleet to be retired as SpaceXAI brings its permitted permanent turbines online.

Portable turbines can be installed quickly, but unlike combined-cycle plants, which can be about

Taylor Logsdon says the turbine noise keeps her children up at night. She later helped to form a neighborhood coalition focused on noise and air pollution.





SpaceXAI's gas turbines rise at the end of a residential street in Southaven, Miss.

1.5 times as efficient, they do not use their waste heat to generate additional power. "By going with this quick and dirty approach there, [the company] is burning more gas, releasing more pollution and contributing to climate change far more than it needs to be," Cohan says.

SpaceXAI did not respond to repeated requests for comment.

The strategy had already been tested across the state line. In Memphis, xAI was relying on temporary gas turbines at Colossus 1 by 2024. The site sits in South Memphis, where the surrounding neighborhoods are predominantly Black and ringed by industry that long predates xAI. After public pushback, xAI applied for a permit for 15 permanent turbines in

early 2025, but four months later two flyovers by the Southern Environmental Law Center, or SELC, found 35 turbines operating there. After the center threatened to sue, the Shelby County Health Department approved the 15-turbine permit. The dozens of temporary turbines at Colossus 1 disappeared around the same time similar machines began appearing in Mississippi, according to an SELC attorney. In an [April letter](#) to the EPA, Senator Sheldon Whitehouse, ranking member of the Senate Committee on Environment and Public Works, quoted an xAI senior manager who described the plan as copy and paste from Colossus 1.

In May the NAACP and its Mississippi State Conference sought a preliminary injunction, arguing that



33 unpermitted gas turbines at Southaven could emit 2,508 tons of smog-forming nitrogen oxides every year. A revised motion filed the next month put that scale in local terms, estimating that the site's emissions could amount to about 26 times those of the TVA Allen gas plant. Abre' Conner, who leads the NAACP's environmental and climate justice work, says the organization wanted to make sure other technology companies did not see xAI's approach as an option.

But the fleet kept growing. In January, xAI said it was running 27 turbines for Colossus 2. MDEQ counted 46 turbines at the Southaven site in May, 60 in June and 69 by July—more than double the number the company had publicly acknowledged at the beginning of the year. Forty-two had been

added in 2026, late enough under the agreement's rolling timetable to remain into 2027; the newest could stay through July of that year.

Before settling on Memphis, xAI reportedly considered eight locations around the country. Musk has said the company was told that building a data center from scratch could take up to two years, so it searched instead for a vacant factory that checked all its boxes. It found one in South Memphis: a former Electrolux plant in an industrial park already threaded with power infrastructure.

The turbines supply warehouse-scale buildings filled with racks of servers built around graphics processing units, or GPUs, the chips first popularized by video games and now prized for training and running

AI models. Colossus 1 uses more than 220,000 Nvidia GPUs; Colossus 2 is estimated to use more than twice that amount. Together, Musk has called the facilities the world's biggest AI supercomputer. Under heavy load, each GPU can draw several hundred watts and generate heat that must be removed. Data centers are increasingly shrink-wrapped around the hardware of their moment; in some cases, building anew can be more efficient than retrofitting for a change-over in chips, cooling systems and power demands.

Colossus is best known for training and running Grok, but the facilities are also becoming a business built on selling computing power. In May, SpaceX disclosed a deal under which Anthropic would pay \$1.25 billion a month for capacity across Colossus 1 and Colossus 2, according to the company's IPO filing. The agreement covers approximately 325,000 GPUs and could total more than \$40 billion through May 2029. Grok's training has moved to Colossus 2,

and the company bought an 810,000-square-foot warehouse in Southaven for a third data center, Macrohardrr. In late July, Musk announced another: Minihard in Memphis, with the same GPU capacity as Macrohardrr.

The White House, meanwhile, was pushing AI companies to shoulder their own power needs. In March it rolled out a voluntary Ratepayer Protection Pledge asking AI companies to "build, bring, or buy" the power needed for their data centers and cover related grid-upgrade costs. xAI was one of the signatories. The pledge has no enforcement mechanism, but it encourages the same build-your-own pathway now being challenged in Southaven.

SOME SOUTHAVEN ALDERMEN WOULD TALK about SpaceXAI, but several ultimately directed me toward Mayor Darren Musselwhite. He was harder to find. One alderman offered to buy me lunch if

Krystal Polk's parents built this house on land her great-great-grandparents bought; SpaceXAI's power plant now sits across the road.



I tracked him down. A resident told me the mayor's nickname was Rapunzel because he was always locked away in his tower. After repeated calls and e-mails and two visits to that tower—Southaven City Hall—Musselwhite did not respond.

A picture began to emerge from my conversations of a project that had become hard for local officials to resist even as trust in SpaceXAI wore thin. Mississippi governor Tate Reeves has called the company's more than \$20-billion Southaven expansion the largest private investment in the state's history. In a letter included with the DOJ's court papers, he warned that an injunction could disrupt the state's economy. Southaven's mayor said in January that the buildout could bring more than 100 jobs and about \$60 million in additional revenue for the city, the county and the school system. The city's share, he estimated, would exceed \$20 billion in 2028—nearly a quarter of its main

operating budget. "It's hard for any community to just say no and turn it down," alderman-at-large George Payne said on his way to work as an engineer at the local news station. Speaking more broadly about AI, he added, "I'm scared to death of it, as [are] many other people. But I don't think it's going to go away. You can't stop now."

A few days before the project was revealed, William Jerome, another alderman, signed a nondisclosure agreement—his first—that prevented him from discussing the project publicly before the company announced it. Jerome says the city has nothing to hide, but he would advise other communities to build data centers far from residential areas and to check their local laws before inviting companies in. "I would tell cities to check their zoning because xAI has not done anything illegal," he says. "For one year they don't have to get a permit. So are they unpermitted? Yeah, but they're not illegal."



Jerome and Payne both say they plan to hold SpaceXAI to its promise to build a quieter, permanent facility to house the turbines. “Now that’s what they [the company] are telling us,” Payne says. “Do I believe with 100 percent certainty? I hope so.”

In Memphis, officials have already been learning the limits of nonbinding promises. At a city council meeting, Sarah Houston, executive director of Protect Our Aquifer, a local water advocacy group, described a recycled-water facility xAI had promised to build. Local officials never secured a binding agreement, and construction paused with the project only partly finished. Houston said completing it would cost another \$100 million, less than three days’ worth of payments under Anthropoc’s contract for capacity at Colossus 1 and 2.

“We learned at the same time as everyone else” that the project was paused, Doug McGowen, president and CEO of Memphis Light, Gas and Water, told the council. He said xAI had restructured, with an entirely new engineering team in place. SpaceXAI’s president told him and Memphis mayor Paul Young that construction could restart in the first quarter of 2027.

Tannera George Gibson, the city attorney, dismissed Houston’s presentation as “cute” and said the city needed to rely on lawyers, not advocates, for information. Pressed further, Gibson acknowledged

that Memphis was leaning on “goodwill and corporate partnership.” Council member Jeff Warren said that the public wanted more accountability. “xAI has had the opportunity to develop these facilities in ways that don’t use water and put water back in cleaner than they take it out, and they haven’t chosen to do it, because they’re in a race against time,” he said.

LOCAL RESISTANCE HAS SPREAD almost as quickly as the data centers themselves. KeShaun Pearson, president of Memphis Community Against Pollution, has spent months traveling through Tennessee, Georgia, Mississippi and Arkansas, trying to turn scattered fights over power and pollution into a Mid-South coalition.

I met him at a barbershop in a strip mall near Memphis’s Frank C. Pidgeon Industrial Center as pink light began to streak the summer sky. He had flown from Atlanta that morning after attending a DeKalb County Board of Commissioners meeting that extended the community’s data center moratorium through September 30.

At least 15 states have considered restrictions or pauses on new data centers, according to the National Conference of State Legislatures, but about half of those proposals have failed. Maine lawmakers passed an 18-month moratorium in spring 2026, but Governor Janet Mills vetoed it. In July, Kathy Hochul,

Polk says SpaceXAI never came to the door before building nearby. After company representatives questioned family members near the property, she and her children began carrying tax records to prove it is theirs.



governor of New York State, signed an executive order making hers the first state to impose a state-wide pause for new large data centers. Local governments, including DeKalb County, have often been quicker to impose temporary pauses of their own.

Pearson grew up near the industrial park in South Memphis with severe allergies. In a letter opposing the permit for gas turbines at Colossus 1, the Asthma and Allergy Foundation of America warned that the project could add health risks in a region already overburdened with asthma and other respiratory problems. A report published in 2026 showed that Shelby County, which includes Memphis, had received an F from the American Lung Association for its high-ozone days for three years running, from 2022 to 2024. DeSoto County, home to Southaven, also received an F for high-ozone days. Now 37, Pearson said communities like his continue to be treated as “the path of least resistance”—as if their lives do not matter—and “strategically targeted for pollution projects.”

Together we drove toward the industrial park. The unfinished recycled-water facility was marked by two large storage tanks. Across from it sprawled a rail yard and the TVA Allen Combined Cycle Gas Plant, an older answer to the question of who controls power here. Congress created the Tennessee Valley Authority in 1933 to bring electricity and flood control to a struggling region, an experiment in public power that Memphis voted to join the following year. The city became TVA’s largest customer; the relationship has repeatedly frayed over waste, water and power costs. Beyond the plant stood the Nucor steel mill, a cornfield and the Mississippi River.

In the heart of the industrial park sat Colossus 1. “It’s so easy for me to see just how our federal government is being leveraged against us,” Pearson said, referring to the DOJ’s effort to intervene in the Southaven case.

After enormous public pushback against SpaceXAI, Memphis created a community-benefits ordinance. Under it, 25 percent of property-tax revenue from the company’s facilities, up to \$100 million, will go toward public-benefit projects in zip codes within a five-mile radius of two of its sites, with 1 percent set aside for environmental work. The ordinance cut against the way Memphis usually courts industry: companies typically negotiate deals that can reduce their property taxes by as much as 75 percent for a set term, but xAI, by Young’s account, asked for no such break. Pearson, however, wants more than money. He wants a moratorium.

In August the Memphis City Council gave initial approval to a temporary pause on new data centers. But for now, the momentum in Southaven is run-

ning the other way. The temporary turbines have a negotiated exit schedule, but SpaceXAI has permission to replace them with a permanent power plant. Environmental groups are challenging that permit, and the legal fight over the temporary fleet is still unresolved.

BACK IN SOUTHAVEN, KRYSTAL POLK, 52, OWNS a home close to the fence line, facing the gas plant. Her great-great-grandparents purchased the land, and her parents built the house at a time when few Black families in the area owned property, Polk says. Intruders once wrote “KKK” in the gravel outside the one-story ranch house.

Still, Polk’s family found peace there, watching big owls swoop down and falling asleep to the rustle of two acres of trees. Her three kids grew up spending weekends there while the family lived at another

In Colonial Hills, the stakes are simpler: who gets the power and who breathes the exhaust.

house in town during the workweek. She hosted gatherings there for dozens of relatives. But this year, on the Fourth of July, she canceled a family get-together because the plant was too loud and the prospect of air pollution was too unsettling. “I feel like we are invisible,” she told me from a couch in her living room, her blue dress brushing the floor. “A whole community is saying the same thing, and they’re not listening to them. They have children and babies over there, and elderly, and it’s very heartbreaking.”

Industry is not new to Polk’s family. Warehouses had moved in around the property. Years earlier, TVA representatives visited the house several times to make sure the family knew the utility was building a gas plant nearby and to hear any concerns. Polk said she remembered them as being friendly and respectful.

TVA had come to the door before it began building; xAI never did. Polk said company representatives have instead repeatedly stopped members of her family near the property, asking why they were there or what they were doing—especially when she invited advocates or reporters onto her lawn. “I have to remind them that this is mine,” she said. “I’m not on your property. This is my property.” She and her kids now carry tax records to prove it. “We will be someone’s study eventually,” Polk said. “It’s probably not this year, but as the years go on, we will be the casualties from all of this.” ●



Cognitive Fatigue and the Choices We Make

Researchers have observed the brain areas that engage when we weigh effort against reward, even when we feel mentally tired **BY VIKRAM CHIB**

T HIS SCENARIO WILL FEEL FAMILIAR to many parents: Imagine spending the day watching your kids—making them breakfast, settling arguments, answering their questions and trying to keep them from getting bored. By the end of the day, you finally take a moment to think about what to make them for dinner and, with it, whether you have the ingredients, how long it will take and whether your kids will even eat it. After an exhausting day, even simple tasks like making a meal can feel overwhelming.

That sensation is cognitive fatigue, and it can come up in all aspects of life. It's the reason that an office worker performing menial computer tasks all day may feel too tired to go out with friends after work. And it's also why a nurse who has just finished a long, demanding shift might opt against making one extra patient visit despite initial plans to check on someone.

In research from our team at Johns Hopkins University and the Kennedy Krieger Institute, my colleagues and I took a [closer look](#) at what happens in the brain when people are faced with decisions while mentally exhausted. This sense of cognitive fatigue isn't just about feeling physically tired. Our team has demonstrated that it deeply impacts people's decisions

and willingness to exert effort. We found that repeated mental exertion can significantly decrease people's motivation to engage in challenging tasks, and we pinpointed the areas of the brain that make this happen.

We used functional magnetic resonance imaging to monitor brain activity in 28 people while they first performed cognitively effortful tasks and then decided whether they were willing to exert more mental effort to earn some money. The monetary rewards allowed us to put an exact dollar amount on people's motivation in different states of fatigue.

While in the brain scanner, participants answered questions designed to test their working memory—a form of memory that allows people to hold multiple ideas in the brain at one time. Participants were asked to recall strings of letters, with varying degrees of difficulty. After we'd gotten our participants warmed up and a bit worn out with these tasks, we gave them a choice between an easy memory test with a \$1 payout if they succeeded or a harder memory test in which they'd earn up to \$8 for answering correctly. As participants became more cognitively fatigued, they were much less likely to choose the more demanding option, even though it could pay more. This decision let us understand how cognitive fatigue can make people value possible rewards versus greater effort.

So what happens in an exhausted brain that makes us behave differently? It turns out there's a decision-making brain system that specifically takes levels of fatigue into account. As people completed ever more exhausting memory tasks, an area at the front of the brain called the dorsolateral prefrontal cortex sent out increasingly strong signals to the right anterior insula, a region toward the middle right of the brain that is known for monitoring how the body is feeling—including levels of fatigue. Based on the patterns we were seeing, we used signals between these two brain areas to compute a person's willingness to trade cognitive effort for reward. As

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people got more mentally exhausted, the activity between these two brain regions increased, meaning more and more signals were sent between the dorsolateral prefrontal cortex and right anterior insula. That greater connectivity between brain regions predicted a person's being less inclined to take on the tougher memory task.

These findings can help us examine cognitive fatigue, both as it's experienced in daily life and in certain conditions in which its effects are most pronounced, such as depression, long COVID and multiple sclerosis. Much remains unknown about severe mental exhaustion, but our research offers a way of learning more. For example, it's possible that people with depression might approach decision-making differently when experiencing cognitive fatigue. And identifying specific neural circuits related to cognitive effort in depression and other conditions could eventually also lead to the development of medications and therapies that target these brain pathways.

Together, the brain systems we have studied help to determine whether a reward feels worth the effort. These fatigue signals have likely evolved to protect us from overtaxing our cognitive and physical systems. When fatigue signals are magnified, so, too, are the costs of exerting more energy.

But there are ways to push ourselves, even when we're tired—and situations in which that extra push is worthwhile. Cognitive fatigue can often stop us from performing activities that might replenish our mental resources, such as taking a walk in the sunshine after work. And even after a long day at work or taking care of loved ones, there are still effortful but important tasks we may need to tackle, such as making healthy meal choices. Knowing the importance of an activity or finding it interesting can spur us past certain feelings of fatigue, research has shown. In other words, thinking about these activities in ways that reframe what you're doing and why it matters can help you go that extra step. ●

Future Moon

The moon is Earth's constant companion. But will that always be the case? BY PHIL PLAIT

EVERY TIME I SEE THE MOON in the sky, it makes me happy. Our natural satellite is so familiar it's easy to take it for granted, but in fact it's an amazing sight. Much of its history is written on its face, with huge dark spots marking where ancient gigantic impacts scarred its surface, still visible after billions of years.

But what of its fate? What will happen to the moon in eons hence? That future is tied up in how it formed, how it's gravitationally linked to Earth and, in the end, what the sun has to say about all this.

The big picture of the moon's origin is fairly well established. Several tens of millions of years after Earth formed, a large planet-size object slammed into our nascent world, delivering a glancing blow that blasted vast amounts of material into space. This ejecta—a mix of Earth and the giant impactor—coalesced to form the moon.

Back then, the young moon was extremely close to Earth, around 20,000 kilometers away—much nearer than its current average distance of 380,000 km. The moon would have been enormous in Earth's sky, about 10 degrees across—roughly the size of your fist held at arm's length.

That soon changed, however. Earth's gravity had a huge effect on the nearby moon, creating immense tidal forces. In a nutshell, the force of gravity weakens rapidly with distance. This means the side of the moon closer to Earth feels a stronger gravitational force from the planet than the side farther away. This change in force across the moon's 3,400-km diameter stretches our satellite from a sphere to a subtle egg shape, with Earth-aligned bulges on the nearside and the farside.

When the moon first formed, it was

also rotating rapidly. And because of inertia, this spin swept the tidal bulges slightly ahead of the imaginary straight line between it and Earth. Our planet's gravity, however, yanked on the bulges, trying to align them once again. This slowed the moon's rotation, lengthening its "day"—and some of the energy lost as the moon's spin slowed was transferred to its orbital motion, moving the moon away from Earth. That recession was initially quite rapid but ebbed as the moon moved farther out and the tidal force diminished. Eventually the moon's spin slowed so much it matched how long the moon takes to orbit Earth once. This is called tidal locking and is why we see essentially just one face of the moon today.

But the moon also exerts tides on Earth, raising two bulges on the planet. Earth's rotation sweeps them out of alignment as well, with the moon yanking back on them, gradually slowing Earth's spin. So our day is getting longer ... but only by about two milliseconds per century, so no need to reset your clock. Still, this effect adds to the enlargement of the moon's orbit, so that even today, billions of years after it formed, the moon recedes from Earth at a rate of about four centimeters per year.

Put all this together, and extrapolating the moon's fate seems simple: it will keep receding, more and more slowly, until eventually Earth's rotation matches the moon's orbital period. At that point *Earth* will always show the same face to the *moon*, and for an observer on the planet, the moon will never rise or set, always appearing in the same place in the sky.

If it ever happens, that is. This process would take billions of years to play out, and we may not have that long.

Earth's oceans play the dominant role

in this grand gravitational process. They absorb most of the energy from the moon's tidal force, sloshing around and creating friction that slows Earth's rotation. But those oceans won't last forever.

The sun is heating up. This is a natural outcome of how our star generates energy by fusing hydrogen into helium. That helium "ash" is building up in the sun's heart, getting compressed and ever hotter as it accumulates, which makes the sun shine brighter, which in turn heats up Earth. In about a billion years, give or take, this will make the Earth so hot that *the oceans will literally boil away*, leaving behind a parched, barren world.

Besides the obvious problems these circumstances pose for life on Earth, the lack of oceans would dramatically slow

any subsequent tidal evolution. The moon's recession would wane, as would the change in Earth's spin rate, adding many billions of years to the timescale—time the sun does not have.

Six billion to seven billion years from now, the sun will run out of hydrogen fuel in its core and swell into a red giant. Scientists argue about whether it will expand enough to engulf Earth, but that's fairly irrelevant to the point here; the moon and Earth will be cooked, and the ultimate tidal fate of our constant lunar companion will be the least of our problems.

Eventually the sun will shed its outer layers, losing about half its mass, and the exposed core will become a white dwarf, slowly cooling over billions of years. That's not the end of the tidal story, though: the sun raises tides on Earth as well, and the current

effect has about half the strength of the lunar tides. The physics of how this solar tide will work on the Earth-moon system in the distant future, however, is quite complicated and not fully understood. The loss of solar mass means the effects will be smaller, too.

On the other hand, by then we'll have nothing but time; over the eons the white dwarf sun's tides may yet destabi-

lize the moon's orbit, pulling it free from Earth or possibly causing it to collide with our planet. Either way, at that point it will hardly matter to our broiled world.

Which is it? We may just have to wait and see. This

situation won't occur for tens of billions of years, which in the potentially infinite future of the universe is like a single tick of the cosmic clock. Better enjoy your view of the moon now while you can. ●

Phil Plait

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

A crescent Earth sets behind the farside of the moon in this image captured by astronauts during NASA's Artemis II lunar flyby in April 2026.



NASA

Broken Thoughts

By Ella Dershowitz

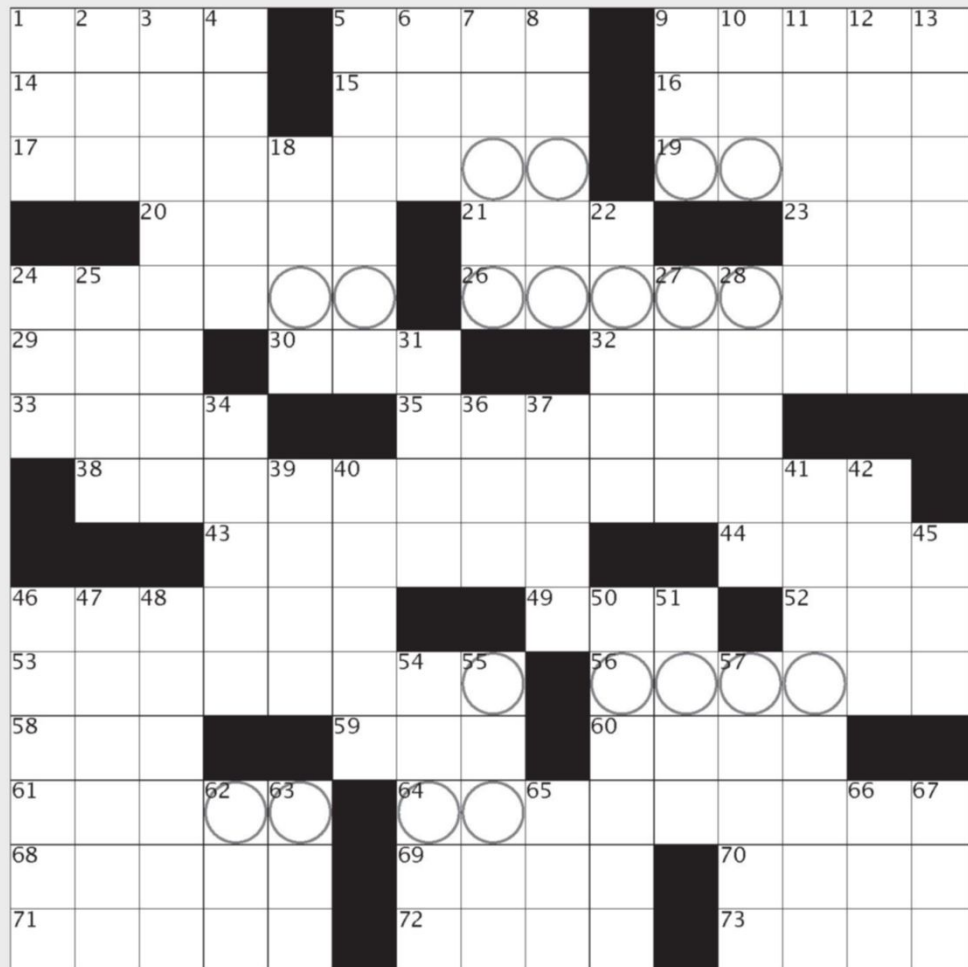
Across

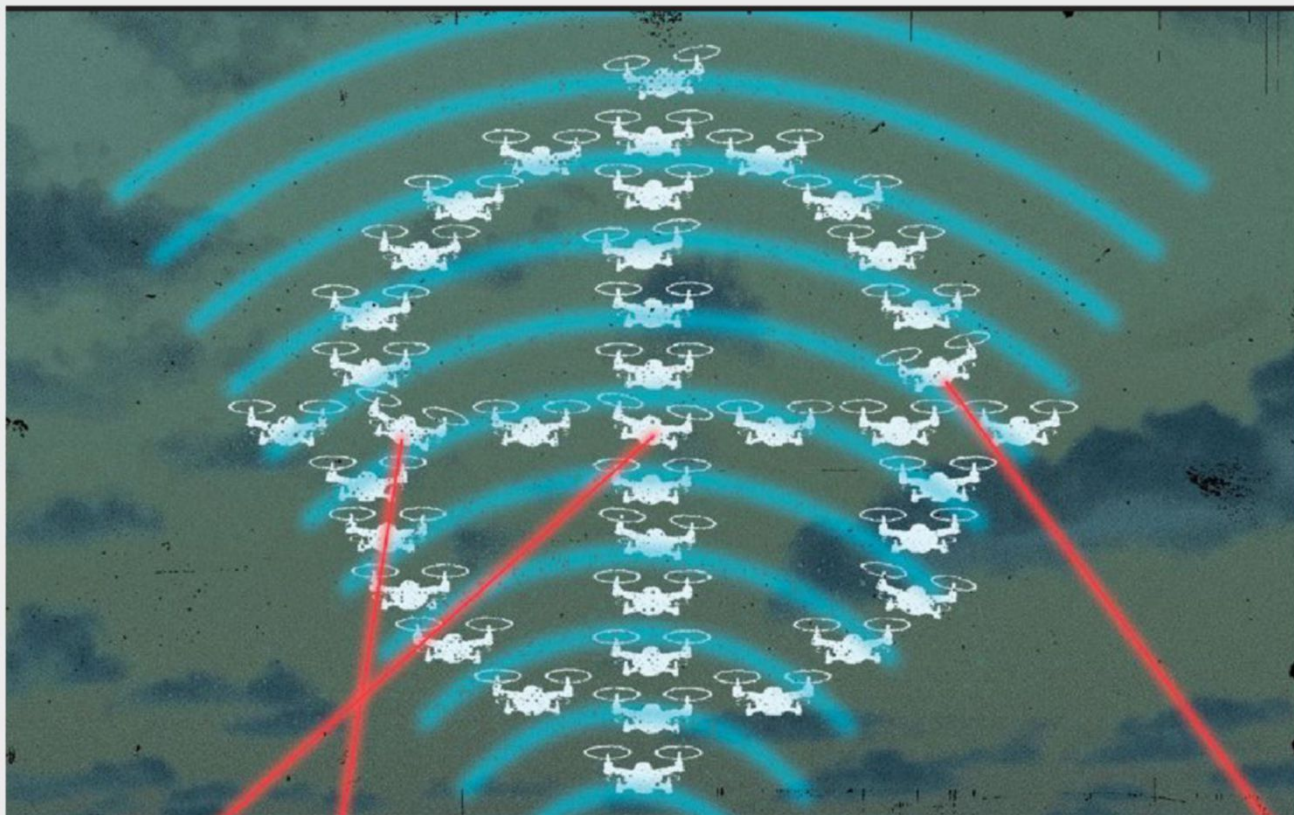
- 1 Arthropod's taste organ
- 5 Unique features of trees that scientists use to "fingerprint" apple varieties (abbr.) (page 62)
- 9 Ukrainian port city
- 14 Boo-boo
- 15 Trattoria exit line
- 16 Combines at high temperature and pressure
- 17 Tool that helps you solve this puzzle, supposedly
- 19 ___ length (lens measurement)
- 20 Fastest-recycling Great Lake (every 2.6 years)
- 21 One of two current MLB Subway Series teams
- 23 Stylistically inspired by
- 24 Reason for optimism
- 26 Downward spiral
- 29 Unruly head of hair
- 30 What the credits aren't in some movies
- 32 Dormant but could develop
- 33 Lead-in to fall but not autumn
- 35 Lady Gaga album (and middle name)
- 38 What unanswerable questions force us to make peace with—as depicted four times in this puzzle (page 28)
- 43 One with a big book bag?
- 44 World's natural solar panel
- 46 2 cute
- 49 Obamacare, initially
- 52 Ill, in modern Rome
- 53 Like kosher hot dogs
- 56 Plays the role of
- 58 Pop singer Rita
- 59 Indian lentil stew
- 60 Spirit made only from sugarcane juice
- 61 Most common female baby name in America from 1947 to 1952
- 64 Felines with M-shaped forehead marks
- 68 Bottom-fermented beer
- 69 Catalan surrealist Joan
- 70 Kringle or Jenner
- 71 Hour experienced twice on the first Sunday in November
- 72 First name in starships

73 Eponymous megafan

Down

- 1 Citizens' rep
- 2 Chemical reaction reaction, perhaps
- 3 Maximal age that may or may not be extendable (page 38)
- 4 Namesake of a nonculinary dish
- 5 Preinterview phone call
- 6 Film's Vardalos
- 7 Capture on a canvas
- 8 Name in *War and Peace* and *Uncle Vanya*
- 9 Like food that doesn't pass the smell test
- 10 Set of orbiting black holes before they merge (page 15)
- 11 ___ velocity
- 12 Entrap
- 13 Like a frame in need of a level
- 18 Patiently wait
- 22 Christopher Robin's creator
- 24 Call a Sox game
- 25 Legislative additive
- 27 Singer k.d.
- 28 Co-opt, as an ancient isopod might do to a bacterial gene (page 20)
- 31 Worked a rave, perhaps
- 34 Former Yankees manager Joe
- 36 Words of affirmation?
- 37 Taj Mahal home
- 39 Next-generation space telescope
- 40 Shined a light on?
- 41 Adoption superstore
- 42 Lee of the dessert aisle
- 45 Urban namesake of a tasseled hat
- 46 Program responsible for around 200 tons of "lunar litter"
- 47 So-called king of fruits
- 48 Sought-after egg yolk color that can be faked by feeding hens paprika (page 88)
- 50 Feast for some fog-dwelling bacteria (page 8)
- 51 In need of a massage
- 54 Wonderland invitation
- 55 Medieval ball and chain
- 57 Some straightforward (or backward) gymnastics flips
- 62 Ones taking LSD?
- 63 Semiconductor designer
- 65 Fam boy
- 66 *Madre's hermana*
- 67 Target of ID thieves





Swatting the Drone Swarms

Cheap drones are draining expensive missile defenses. Lasers and microwaves could reset the contest, if they can escape the test range **BY SARAH SCOLES**

IN JUNE, DEFENSE SECRETARY Pete Hegseth visited White Sands Missile Range in southern New Mexico. This stretch of desert had been a proving ground for barely a week when, in 1945, Manhattan Project scientists detonated the first atomic bomb at its Trinity Site, releasing the destructive energy of nuclear fission. Nearly 81 years later White Sands hosted a different experiment in concentrating electromagnetic energy: a demonstration of lasers and high-power microwave weapons designed to take down drones.

When operators fired a U.S. Army prototype based on Epirus's Leonidas system at a swarm of 12 drones, all of them dropped from the sky. Invisible microwaves had disrupted the electronics that kept them aloft. Hegseth himself took control of another system, called LOCUST, and used its high-energy laser to defeat a drone.

Directed-energy weapons have long been more promise than combat reality, with technologists dreaming big yet

fielding few systems. Cheap drones might have given them a practical use.

Drones can gather intelligence on troop movements and strike those troops. But traditional U.S. defenses do not always match the threat. Drones are now inexpensive and ubiquitous; the missiles used to take them out are often much costlier and limited in supply. A defense can work while losing the economic and logistical contest. "The protectors—which are built to hunt lions or elephants—are getting kicked in the butt by the mice," says Andy Lowery, CEO of Epirus. "Mice are coming in, and so what we do is we defend against mice." He hopes Epirus's microwaves can provide that defense—a mousetrap, he calls it.

The Pentagon knows it needs a solution to the mouse problem. Drones are central to the wars in Ukraine and across the Middle East. They're also a stateside threat: anyone can buy them online and send them toward a military base or large gathering. "Small unmanned systems are a defining threat for our time," says Army Lt. Col. Adam Scher, quoting General Matthew Ross.

Sarah Scoles

is a Colorado-based science journalist and a contributing editor at *Scientific American*. Her newest book is *Countdown: The Blinding Future of Nuclear Weapons* (Bold Type Books, 2024).

"They are prolific, they're evolving quickly and they're no longer confined to combat."

In August 2025 the Defense Department established Joint Interagency Task Force 401, a unit dedicated to counterdrone innovation. Scher is its strategic communications adviser. Directed energy—lasers that burn through drones' hardware and microwaves that essentially fry them—is part of the unit's strategy.

Task Force 401 has selected five U.S. bases, in Arizona, Texas, Washington State, North Dakota and Missouri, for a directed-energy pilot. According to Scher, the program will let operators give feedback on the systems' performance and help to shape future doctrine and training. It will also help the military coordinate with the Federal Aviation Administration when using lasers and microwaves in domestic skies. Scher says the task force is working hard to get directed-energy systems into the field "rapidly."

IN FEBRUARY, Customs and Border Protection (CBP) used LOCUST near Fort Bliss in Texas against what officials believed was a threatening drone. The object might have been a Mylar party balloon. Because the firing had not been coordinated with the FAA, the agency closed the airspace around El Paso International Airport. Two weeks later the U.S. military used a laser near Fort Hancock in Texas to shoot down another object it deemed threatening. The drone belonged to CBP.

The next month the Pentagon and FAA tested LOCUST together at White Sands to evaluate how it could operate around civilian aircraft. Leonardo DRS, a defense contractor, has also integrated LOCUST into a Stryker armored-vehicle prototype, combining the laser with systems that can track and identify drones.

The army's interest in directed-energy systems isn't new, says Philip Perconti, Leonardo DRS's senior vice president and chief technology officer. He would know: he was previously dep-

uty assistant secretary of the army for research and technology and the army's chief scientist. But that interest hasn't necessarily translated into operations.

"When you want to build exquisite optical systems with high-energy, high-end laser power, it's not so simple," Perconti says. Lasers have historically been princess-and-the-pea instruments, precise and particular about their operating conditions. Engineers have had to ruggedize them without disrupting the optics and power systems that make them work, then mount them on, say, tanks instead of keeping them in the laboratory.

The aircraft dotting the sky simply stopped and fell nearly in unison, like dancers dropping on cue.

Getting a laser onto a tank does not mean it can hit the right things, especially when those things are drones. "These are small, fast-moving targets that can be coming at you, or they can be moving laterally to you," Perconti says. "They're very hard to detect." The LOCUST-equipped Stryker uses radar to detect and track drones. An infrared system then identifies the aircraft. "Only then is the laser engaged to bring the thing down," he says.

That is a gory process. "You're literally cutting into the target, so you have to hold the laser on the target for some period of time to allow it to either melt the plastic or cut through the metal," Perconti says. "People don't realize you can do that with light, but then you go out in the sun and you get a sunburn." Leonardo DRS is working to put that burn on systems that are more mobile and better able to engage multiple drones in quick succession.

TAKING ON SEVERAL DRONES at once is Epirus's specialty. Unlike a laser, a microwave weapon can spread its effects across a wider patch of sky. In August 2025, Epirus says, its Leonidas system

defeated a swarm of 49 drones with a single pulse. The aircraft dotting the sky simply stopped and fell nearly in unison, like dancers dropping on cue.

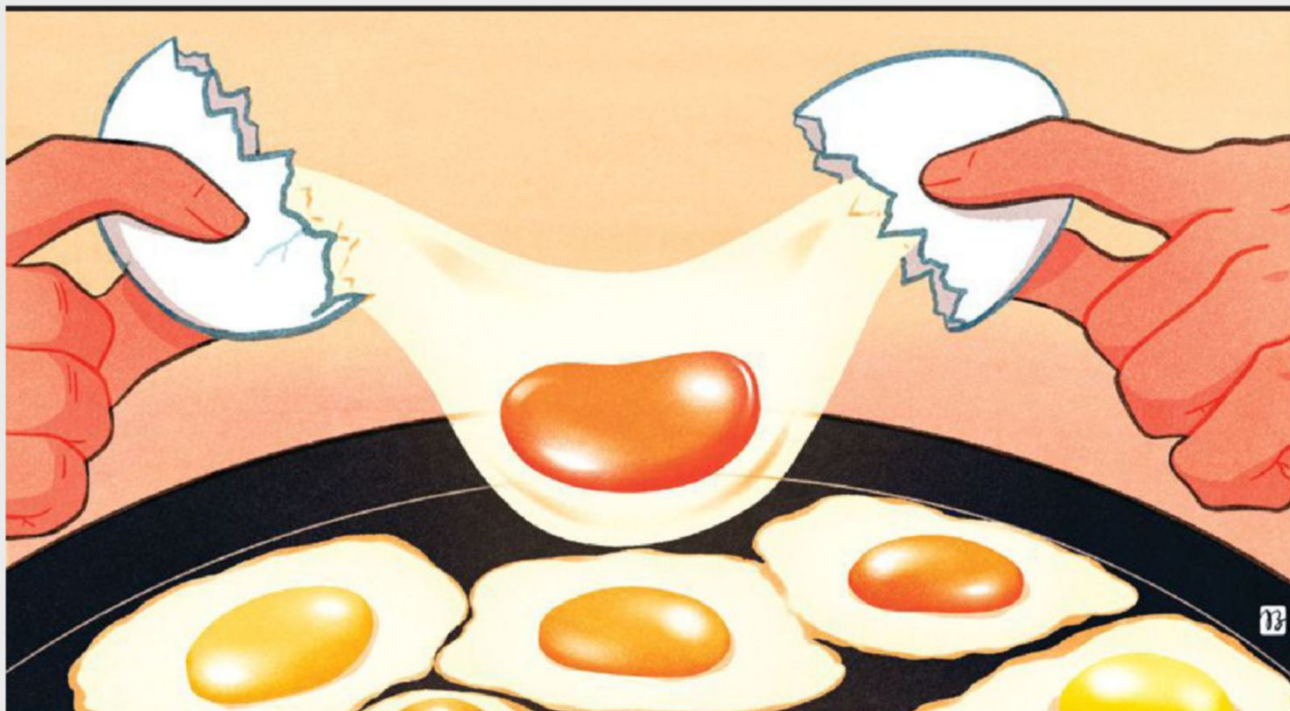
The idea for Leonidas grew out of Lowery's time at Raytheon. There he noticed what he calls a "fratricide effect" from shipboard radars the company built. "You get within two or three kilometers of shore, and you start knocking out different electronics—you know, radio stations, television stations, even cellular towers," Lowery says. "And so you have to drop the power." Nobody wants the U.S. Navy knocking their sitcom off the air mid-laugh track. He

wondered why engineers were not studying how to weaponize that interference. When he left to start Epirus, the company team decided to do so itself.

Leonidas creates microwave pulses that last milliseconds—a long time in directed-energy terms. "We've never been overflowed; nothing has ever gotten away," Lowery says of the company's tests. Some drones have come within about a football field of Leonidas before the system disabled them. Like Leonardo DRS, Epirus plans to make its weapons more mobile.

Neither lasers nor microwaves will defend a base or battlefield alone. Drones require a layered defense, an onion of options—kinetic and directed energy, long range and close-in, things that melt, burn or scramble electronics.

The U.S. is not only a drone counterer. It's also a drone operator, so it will have to protect its aircraft against systems like those that companies such as Epirus and Leonardo DRS are building. Drones require counterdrone weapons, which invite counter-counterdrone weapons. At White Sands, the cycle is hard to miss. ●



What Egg Yolk Color Really Means for Health

Deep-orange yolks could have a slight health benefit, but it's easy for egg producers to "fake it"

BY LORI YOUMSHAJEKIAN

MANY EGG LOVERS believe a glossy, sunset-colored yolk is more nutritious than a pale-yellow one. The color has become shorthand for high-quality and highly nutritious eggs that come with a much higher price tag. But color is actually one of the easiest things about an egg to manipulate with just a few tweaks.

With the right feed, egg producers can fine-tune yolk color on a spectrum from pale yellow to orange and red. The shade of the yolk is determined by carotenoids—plant pigments that are found in many foods, even bugs. And there is some

evidence that certain carotenoids influence eye health in humans. Whether you should shell out for darker yolks, however, seems to come down to personal preference.

A hen's digestive system pulls carotenoid pigment out of whatever the bird eats, and that pigment eventually gets deposited in the egg yolks. "That is what gives us the deeper color," says Darin Karcher, an animal sciences professor at Purdue University. The most common of these carotenoids are xanthophylls, found in dark leafy greens, peppers, corn and even algae. Eggs from pasture-raised hens can lean more orange be-

cause the birds have access to bugs and greens loaded with xanthophylls that a typical wheat-and-barley feed lacks. The shade can shift with the seasons because hens might forage more during the warmer months.

But a darker yolk doesn't necessarily mean a hen spent its life pecking around outside. Producers can "fake it" by adding certain foods rich in xanthophylls to the typical feed, says Stephan van Vliet, a nutrition scientist at Utah State University. Marigold petals or paprika can yield orange yolks—Vital Farms and other egg producers add these supplements to their feeds to deepen the yolks of their pasture-raised hens. On the other end of the spectrum, the addition of cottonseed meal can turn yolks an unappetizing olive green.

Egg producers will make changes to match the sensory expectations of consumers. Producers also want to keep yolk color consistent no matter where their eggs are sold, van Vliet says, and they rate them on a 16-shade yolk scale from palest to darkest orange, which is called the YolkFan. Research into consumer preferences by DSM-Firmenich, the company behind the scale, has shown that most people

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globally seem to prefer yolks with a darker orange color.

But whether it comes from paprika additives or foraged greens, the pigment in the eggs you eat may still benefit your health. Xanthophylls such as lutein and zeaxanthin reach the retina and accumulate as macular pigment, possibly slowing age-related macular degeneration, says Elizabeth Johnson, a nutritional biochemist at Tufts University.

In a study comparing similar doses of lutein from supplements, spinach and lutein-enriched eggs, Johnson and her colleagues found that the egg-sourced lutein was better absorbed by the body. This may be because the naturally occurring fat in the yolk helps eggs deliver the compounds especially well—the same reason a [spinach salad](#) drizzled in a fat, such as olive oil, is also a good source of lutein.

Even though eggs raise blood levels of lutein, their ability to improve vision or reliably increase the density of macular pigment [has been inconsistent among other studies](#). Macular pigment, [which filters](#) blue light and acts as an antioxidant in the retina, [increased meaningfully](#) in older adults who were fed four eggs a day for a little more than a month. But some studies haven't found that consuming eggs changes macular pigment density, and unlike vitamins or minerals, lutein [isn't considered an essential nutrient](#).

Any health claims that companies make about darker yolks should be treated with caution—such claims require demonstrating a clear health benefit for humans, Karcher says, which is a bar that has not yet been cleared. Van Vliet recommends choosing pasture-raised eggs because they are likely to have come from the happiest and healthiest hens—the ones seeing sunshine, having space to roam and eating a more diverse diet.

"If you know where your eggs come from, what they were fed," van Vliet says, "that's probably more important than just going by color." ●

THE GOLDEN RECORD

isn't fully golden. It's two gold-plated copper discs engraved with Earth's sights and sounds and welded to Voyagers 1 and 2. Back then I saw their process on the news and I wanted to be on that committee—one of the people who decided what aliens should hear: the ocean, bird caws, violins, a baby's laugh, hyenas, volcanoes, traffic, fifty-five languages and six full seconds of mud pots glugging. Elementary-school me wouldn't have pushed the mud pots, maybe leaned into koalas and monorails, but still, I wanted to be Carl Sagan's heroic secretary who canvassed all of Ithaca and beyond to rally native speakers fast, pre-Internet, and carve their voices into metallic grooves in that I-want-to-teach-the-world-to-sing spirit that floated like a rainbow tie-dyed gasoline spill on the surface of the dark water of the 70s.

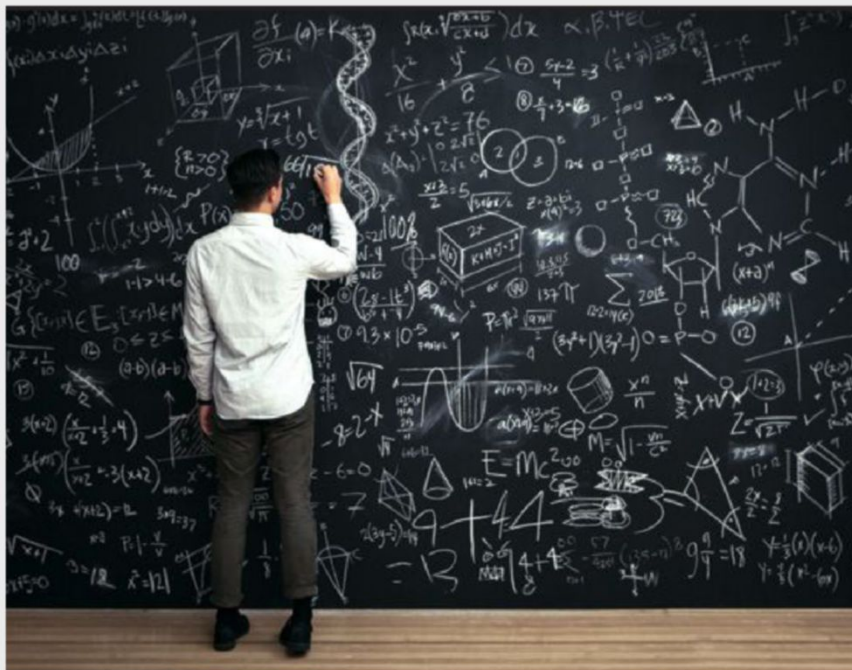
On the assumption aliens had eyes, the committee included pictures: cell division, a grape-picker, mushrooms, x-rays, rickshaws, a woman licking a chocolate ice cream cone, a man grimly eating a sandwich, and another man drinking from a pitcher as if he had been lost in the desert for days, an unpleasantly voracious triptych that might make a more refined life-form wince.

The records are still out there more than 11 billion miles from Earth and 40,000 years from another planet, not even close to each other in interstellar space. Along with a needle and hieroglyphic instructions telling them to play it at 16⅔ speed, they'll float on with their hosts indefinitely, until they break apart in the dark or stop transmitting and become, officially, space junk.

Even now, I think I know what people want to hear. Sometimes I give them what I think they want to see: the breathing, thinking messy mammal hidden and refracted into librarian, scientist, polyglot-wrangler, frozen smile even bigger than that Malaysian father holding his daughter, eternally happy in a picture floating in the dark. In my head, I consult with a committee constantly. *Does this sound like static? Are these a code or just random beeps?*

I used to believe if you packaged it just right, anyone could understand you, record player or not. We'll be gone before the gold shows up on what passes for a cosmic doorstep but there's still a chance the aliens might understand we were more than just part of the machinery.

Jennifer Blackledge is a Detroit-area poet who works in the automotive industry. She was awarded the 2025 Zócalo Public Square Poetry Prize. Her work has been published in *JAMA*, *Rattle*, *ONE ART*, *I-70 Review*, *Kestrel*, and elsewhere.



The Fastest Way to Multiply Numbers

A 23-year-old student overturned an ancient conjecture about one of math's simplest operations

BY JACK MURTAGH

ELEMENTARY SCHOOL STUDENTS might memorize their times tables for single-digit numbers, but memorization won't cut it when the teacher asks for three-digit multiplication. This kind of problem requires an algorithm: students are taught to stack one number atop another and multiply each digit of the bottom number by each digit of the top one. For millennia mathematicians believed this to be the fastest multiplication method, until a 23-year-old made a shocking discovery in 1960, which led to a mystery that remains unsolved to this day.

This mystery is critical to anyone who partakes in the digital world because multiplication is a foundational operation for computers. Encryption, robotics, artificial intelligence, and pretty much everything else using silicon chips involves multiplication, sometimes of huge numbers many times over. At this scale even a simple operation becomes a bottleneck, and any extra efficiency has economic consequences.

To understand the nature of the bottleneck, observe how the grade school algorithm handles growth. When you multiply two two-digit numbers, you perform four single-digit multiplications. If you bump that up to a pair of three-digit numbers, you do nine single-digit multiplications. The workload scales

as the square of n , the number of digits. When analyzing such an algorithm, computer scientists don't measure computational speed, because that depends on the hardware. Instead they count the computational steps. They also ignore minor bookkeeping details such as the time it takes to carry a one when multiplying. When numbers get large enough, those lower-level operations cease to matter, entirely eclipsed by the more intensive processes involved.

Computer scientists denote the number of steps with what's called Big O notation: the grade school algorithm, for example, takes $O(n^2)$ steps, which is read as "order n squared." Broadly speaking, if the numbers become twice as long, executing the algorithm takes four times as much computational work. If the numbers are 1,000 times as long, it takes a million (1,000 squared) times as much work.

Since antiquity, mathematicians have suspected that $O(n^2)$ was an inherent speed limit for multiplication. Celebrated Soviet math professor Andrey Kolmogorov posed the $O(n^2)$ speed limit as a formal conjecture and mentioned it during a 1960 seminar at Moscow State University. Whenever mathematicians propose a conjecture, they are planting a kind of flag and waiting for others to either prove or disprove their idea. It took just a week for Anatoly Karatsuba, a student who had been in Kolmogorov's audience, to prove this one wrong. Kolmogorov was stunned. The result was published in the prestigious *Proceedings of the USSR Academy of Sciences*, but amusingly, Karatsuba didn't write it. Kolmogorov wrote the formal proof himself and submitted it for publication with Karatsuba named as lead author. Karatsuba found out about the paper only when he received the reprints in the mail.

Karatsuba's genius was in realizing you can trade expensive, time-consuming multiplications for cheap, fast additions. Adding two n -digit numbers takes only $O(n)$ time because it entails a single sweep through the digits rather than a complete sweep through the top number for every digit of the bottom number, as

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Justin Lewis/Getty Images

in multiplication. To see how Karatsuba traded multiplication for addition, let's look at a brief example. The method would be overly complicated for such a simple problem, but it saves a meaningful amount of time when numbers get larger.

In this basic example, let's calculate 12×34 .

First we split both numbers into their tens and ones digits. Assign $a = 1$ and $b = 2$ for 12, then $c = 3$ and $d = 4$ for 34. Algebraically, we can rewrite 12×34 as $(10a + b) \times (10c + d)$.

Expanding this equation gives $100(ac) + 10(ad + bc) + (bd)$.

To solve the equation in the traditional way, one must perform four distinct multiplications: $ac = 3$, $ad = 4$, $bc = 6$ and $bd = 8$, which is exactly what the grade school stacking method involves. (Note that we don't count the multiplications by 100 or by 10, because for those we would just plop zeros at the ends of numbers.) Karatsuba noticed a brilliant algebraic trick. Once you compute the first and last terms, ac and bd , you can figure out that pesky middle term, $(ad + bc)$, with one more multiplication step rather than two. You don't need to calculate ad and bc individually:

$$(ad + bc) = [(a + b) \times (c + d)] - ac - bd$$

Or, with our concrete numbers:

$$[(1 \times 4) + (2 \times 3)] = [(1 + 2) \times (3 + 4)] - 3 - 8 = 10$$

Pause to notice the weirdness of the equation above. It suggests that to multiply 12×34 quickly, you should add the 1 and the 2 in 12 and the 3 and the 4 in 34. This is hardly a natural thing to do. No wonder it took so long for someone to figure it out. It ends up reducing the workload, however: because we've already computed ac and bd , the right-hand side contains only one more multiplication, plus some additions and subtractions.

Returning to $100(ac) + 10(ad + bc) + (bd)$, we need only three multiplications rather than four. We compute ac and bd in the straightforward way and then use Karatsuba's trick to compute $(ad + bc)$ with a single multiplication. Plugging in

$ac = 3$, $bd = 8$ and $(ad + bc) = 10$ gives our answer of 408.

We shaved one multiplication off the procedure. If that seems measly, Karatsuba has another insight in store. Say we're multiplying bigger numbers: $1,234 \times 5,678$. We split them in half like we did before: $a = 12$, $b = 34$, $c = 56$ and $d = 78$. Then we write the problem as $(100a + b) \times (100c + d) = 10,000(ac) + 100(ad + bc) + (bd)$.

We can solve this equation with three multiplications. Those multiplications, however, now involve two-digit numbers. Luckily, we know a way to multiply two-digit numbers with only three single-digit multiplications each! In total, a problem that would take 16 single-digit multiplications the traditional way now needs only nine. When we recursively use Karatsuba's trick on large numbers, the savings compound. It splits the input numbers in half, then splits those halves in half, and so on, applying this four-for-three trade all the way down. The algorithm works out to have a running time of roughly $O(n^{1.585})$, which is drastically faster than $O(n^2)$. For reference, multiplying a pair of 1,000-digit numbers involves a million single-digit multiplications with the grade school method but fewer than 57,000 with Karatsuba's algorithm.

The student's efficiency is baked into software that runs every day. Because of the approach's extra overhead (the additions, managing the repeated splitting and recombining of numbers, and so on), its advantages over the grade school algorithm don't kick in until numbers grow relatively big. [Python](#), for example, is a programming language that is famously smooth at handling integers of any size. If you peek into its underlying source code, you will see it relies on a hybrid approach. For modest-size inputs, it uses the grade school math, but once numbers reach around 630 decimal digits, it flips a switch and employs Karatsuba's algorithm. That many digits might seem gargantuan by terrestrial standards, but computers deal with [much bigger numbers](#).

(Technical aside: The Python documentation lists a Karatsuba cutoff of

70 digits. But on most modern machines, [Python stores large numbers in base 2³⁰](#), which translates to roughly 630 decimal digits.)

Karatsuba's algorithm ignited a decades-long race to find the ultimate speed limit of multiplication. That pursuit culminated in 2019, when mathematicians David Harvey of the University of New South Wales and Joris van der Hoeven of the French National Center for Scientific Research [described an extremely sophisticated algorithm](#) that beat Karatsuba's by more than any of the previous breakthroughs. The new algorithm runs in $O(n \times \log n)$ time. Here "log" denotes the logarithm of n , which is a function that grows very slowly. It's a staggering result. The function $n \times \log n$ is just a little bit bigger than n itself. This means that calculating the product of two massive numbers requires only a little more time than adding them, or even reading them, would in the first place (it takes n computational steps to read all n digits of a number).

The triumph comes with a crucial caveat, though. Just as Karatsuba's algorithm outperforms the grade school approach only when numbers get reasonably large, the Harvey-van der Hoeven algorithm doesn't pull ahead until the numbers become truly galactic. In computer science, "[galactic algorithm](#)" is a formal term for a method that is impressively efficient on sufficiently large numbers but will never be useful in practice because the numbers are so large.

Even with that asterisk, it was a watershed achievement. It secured the record for the fastest known multiplication method in principle and could pave the way for algorithms that run in $O(n \times \log n)$ steps, not just in principle but in practice. Today theoretical computer scientists widely suspect that $O(n \times \log n)$ is the fastest possible speed for multiplication, and formally proving it has become the holy grail for this niche field of mathematics. But as history reminds us, widespread consensus is not a mathematical proof. Conjectures about the speed limit of multiplication have been overturned before. ●



Unexplainable Questions

Why the biggest questions in science inspire us even when we lack answers BY CLARA MOSKOWITZ

THE MOST FASCINATING QUESTIONS are often the hardest to answer. How did the universe begin? How did life evolve? What is the nature of consciousness? These questions inspired our special package on “Impossible Questions” on page 28, which explores mysteries that are not just unsolved but potentially unsolvable.

Such questions are also the driving force behind the *Vox* podcast *Unexplainable*, which delves into scientific unknowns large and small, from the [nature of dark matter](#) to the [science of human cells](#). The show, which debuted more than five years ago, also premiered as a video podcast on Netflix this summer. Over the years it has investigated mysteries such as [whether plants can see](#), [why humans cry](#), and [what silence sounds like](#).

SCIENTIFIC AMERICAN spoke to *Unexplainable* host Noam Hassenfeld about dangerous unanswered questions, why bicycles are mysterious, and just how much we still don’t know about the universe.

An edited transcript of the interview follows.

What’s the main idea behind the podcast?

Our show launched in early 2021, when the pandemic was going pretty intensely. There were lots of debates about how

science works and how science should work. Something we really wanted to do was be honest that science is made by fallible scientists who have lives and make mistakes and are trying their best. And the most important thing is to be transparent about your mistakes and be open about what you don’t know.

There are some really big questions where we might not be close to answers. [How big is the universe?](#) [How did life start?](#) What’s the point of it all? At the fundamental level, they are all trying to make sense of our existence.

But I don’t think you need to get to the huge cosmic existential questions to have really juicy, unanswered ones. I’ve found that our audience really appreciates finding out things that they don’t know. Like, [we don’t know how bicycles work](#). This is one of my favorite ones.

Wait, we don’t understand how bicycles work?

Yeah. This gets a little bit technical. It’s a question of which physical theory actually explains how bicycles stay up. At a fundamental level, I think there’s no very easy, simple way to explain why they do.

Clara Moskowitz
is chief of reporters
at *Scientific American*.

Wow! And that's a pretty different kind of unanswerable question than, for instance, how the universe began. It's easy to assume that an unexplainable question is existential or cosmic. But we also do a lot of these really prosaic mysteries. So, why do we cry? Or should yogurt be its own state of matter? Or, you know, one of my favorites was an episode about the fact that some people can't burp. These basic questions are unexplainable just as much as the cosmic, where-did-we-come-from questions. Understanding exactly why these questions are unanswered lets us figure out exactly what we still need to figure out, and it also just helps me stop taking the everyday world for granted.

In the course of looking into these questions, have you come across a scientific mystery that seems to be not just currently unexplainable but unanswerable in theory?

I want to say, "Never say never," because as I'm sure you know, many questions were once thought to be unsolvable, and then we figured them out, and we found ways to answer new questions we never even thought we would have.

But one that comes to mind is an episode we did on the question of whether the entire observable universe is inside a black hole. Is the universe just a black hole that is inside another universe that's inside a black hole, that's all black holes all the way down? At a certain level, that question is kind of unanswerable because you can't get outside the black hole. The scientist I talked to suggested building a particle accelerator that would go around the moon. So it's one of those things where maybe it's possible to answer it, if we did the most ridiculous thing imaginable.

Are there some questions that should stay unexplained because trying to answer them would be too dangerous? The classic example might be the work that led to

the atomic bomb. Should we have left those questions unanswered?

That's really tough. I think there are questions where finding the answer can be dangerous, like with the atomic bomb, although that also gave us carbon-free energy. And then there are also questions that maybe we can solve only if we don't do our research ethically. There are things that we've learned in the past through extremely unethical means. Someone once wrote into a Vox advice column asking, in the course of IVF, should I do everything I can to select the embryo that will have the least chance of disease? And then

"It's very easy to go throughout your day and not confront that basic fact that almost everything everywhere is unknown."

—NOAM HASSENFELD PODCAST HOST

how far should I go? Should I select height and gender and eye color? You can see how it really spirals. I think having the impulse to solve things perfectly can both be impossible to meet and maybe lead you to a somewhat dangerous place.

Have you ever felt surprised about just how much we don't know?

I still remember an episode we did talking to researchers about the idea of whether there might have been a technological species before humans, like millions of years ago. We think we have this full picture of the past—we have all these fossils; we know what was going on. But in fact, we've barely found anything. You know, we've mapped less than one third of the ocean floor. We don't really know how smell works. Everything is just way more complicated than it seems. Ninety-five percent of the universe is made up of dark matter and dark energy, so

we barely understand the vast majority of everything.

You don't realize that what we know is like this little candle in the darkness. And when you're right next to it, it can feel like a lot. But then you zoom out, and you realize that we just don't really know that much. It's very easy to go throughout your day and not confront that basic fact that almost everything everywhere is unknown.

Does that ever feel discouraging?

I don't know. On the one hand, it makes me feel that much more grateful for what we actually have discovered. How

we've been able to slowly build this enormous body of knowledge in the face of all the unknowns. It definitely makes me not take that for granted. And I get excited about how much more there is to understand. I know that when I die, we are still going to understand basically nothing that's going on, but we are going to understand more than we do now. And there's a lot of room for everyone who comes afterward to figure more stuff out.

When we started this show, we were like, are we going to run out of unexplainable things? And then very quickly we realized, definitely not. It kind of puts the magic back in the world a little bit. It makes you realize that this world is ridiculously complicated and that so many people are trying so hard to understand it. We've gotten so, so far, right? We have increased the mountain of knowledge to an absurd extent. And we still have so far to go. ●

Ripples in Space and Time

The latest gravitational-wave discoveries include record-breaking cataclysms

TEXT BY CLARA MOSKOWITZ

GRAPHICS BY

LUCY READING-IKKANDA

SINCE GRAVITATIONAL WAVES were first detected, in 2015, physicists have found almost 400 of these undulations in the fabric of spacetime. A new catalog of the findings, released this year, includes waves made by the collision of the heaviest pair of black holes seen yet, plus ripples from a set of black holes that were spinning at about 40 percent of the speed of light before they smashed together.

The collective findings come from a trio of gravitational-wave detectors: the U.S.-based Laser Interferometer Gravitational-Wave Observatory (LIGO), the Virgo interferometer in Italy, and the Kamioka Gravitational Wave Detector (KAGRA) in Japan.

Albert Einstein predicted gravitational waves in 1916, shortly after publishing his general theory of relativity, which describes how gravity molds the shape of space around mass. The collision of massive bodies such as black holes and neutron stars produces such extreme warping of spacetime that the effects are discernible millions or sometimes billions of light-years away.

Researchers are using gravitational waves to test Einstein's theory of gravity in the hope of eventually finding cracks that point toward a deeper theory.

THE ORIGINS OF GRAVITATIONAL WAVES

Gravitational waves are distortions in the fabric of spacetime caused by the motion of massive objects. These waves can reveal extreme cosmic events that produce little or no light.

For example, a binary system of two co-orbiting black holes can emit gravitational waves that radiate energy, causing their orbits to decay and ultimately leading to a merger. The newly formed, more massive black hole then settles into a stable state, and the spacetime distortions subside.



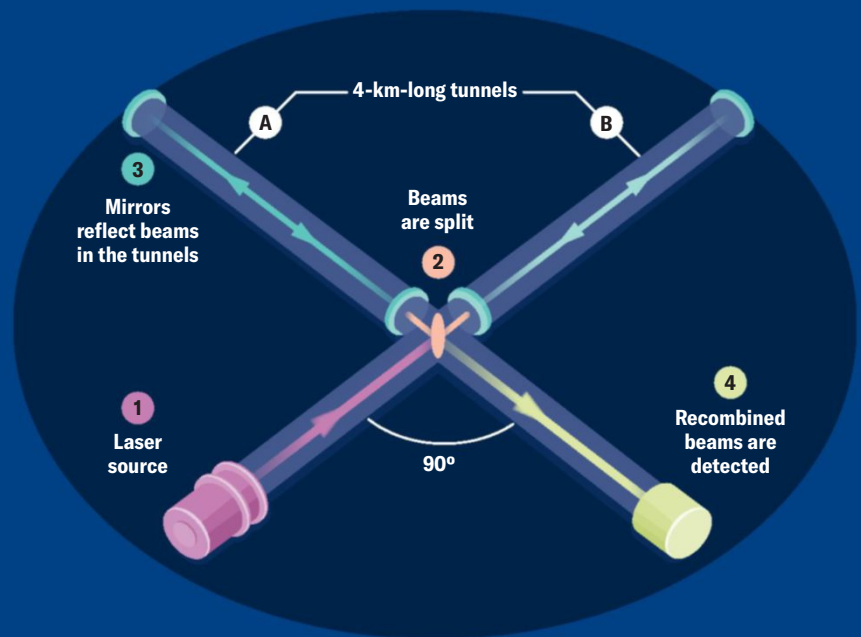
The gravitational waves from such mergers travel outward, carrying characteristic frequencies and amplitudes detectable by sophisticated instruments on Earth.

Gravitational-wave signal



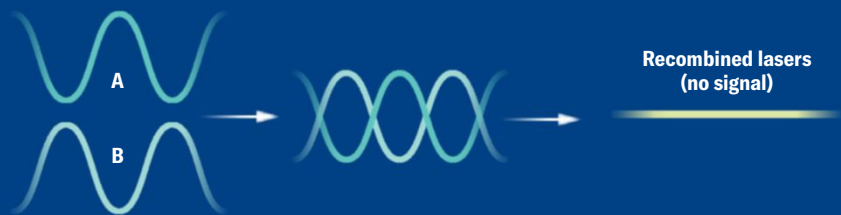
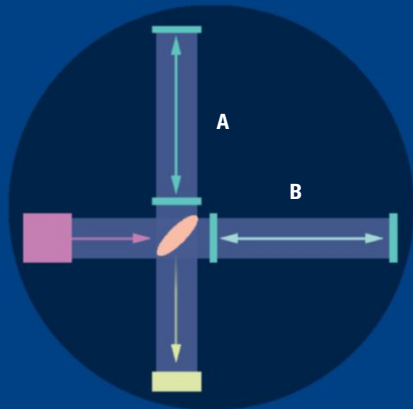
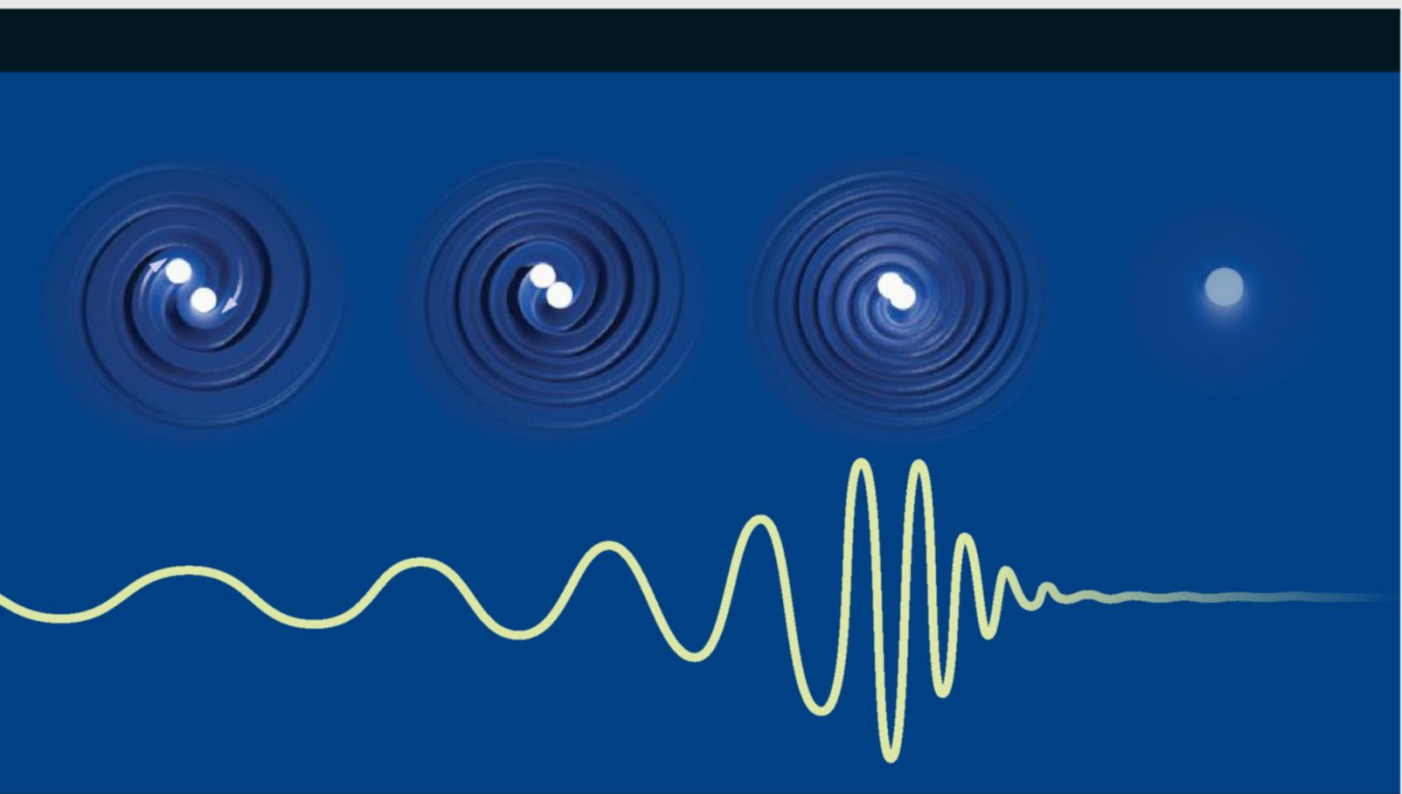
HOW TO DETECT GRAVITATIONAL WAVES

As gravitational waves pass through Earth, they stretch and bend space minutely, creating tiny distortions that experiments can detect.



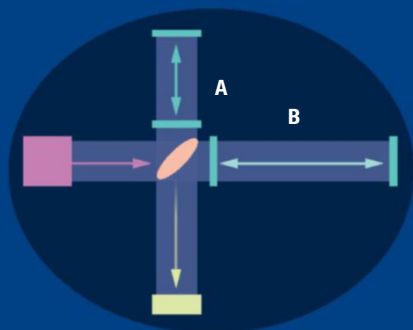
A GIGANTIC RULER

In 2015 the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves for the first time. LIGO operates by splitting a laser beam into two. Each beam travels down its own long tunnel. After reflecting multiple times between mirrors at the ends of the tunnels, the beams are recombined at the detector.

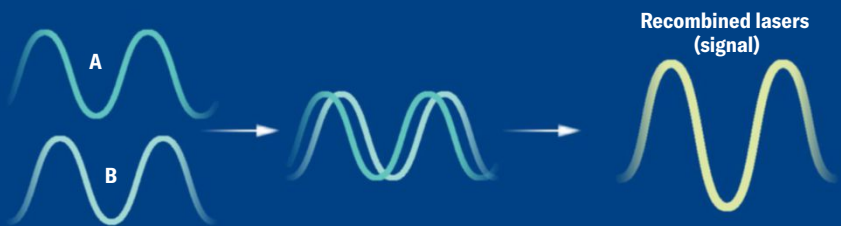


NORMAL OPERATIONS

Under normal conditions, when no detectable gravitational waves are present, the light beams travel identical paths and cancel each other out when they recombine at the detector.



Warped spacetime



EFFECT OF GRAVITATIONAL WAVES

Gravitational waves warp the region of spacetime through which the tunnels run. As a result, the laser beams travel slightly different distances before recombining at the detector, creating distinctive interference patterns that signal a detection.

50, 100 & 150 Years

ERADICATION OF SMALLPOX

1976

"Smallpox, the most devastating and feared pestilence in human history, is making its last stand in two remote areas of Ethiopia, one in the desert and one in the mountains. As of the end of August, only five villages had experienced cases in the preceding eight weeks. More important, the onset of the last known case was on August 9. Because man is the only known reservoir for the smallpox virus, the disease should be eliminated forever when the last infected person recovers." *This article was written by Donald A. Henderson, who was chief medical officer in charge of smallpox eradication at the World Health Organization. Smallpox remains the only infectious disease in humans to be globally eradicated.*

WONDER OF THE COMMONPLACE

1926

"There is nothing in all of nature more wonderful than anything else when we stop to think about it. For not even the most trivial happening can we as yet give any ultimate explanation. It is true that there are many things which we have come to regard as commonplace, but they have lost for us their real wonder only by reason of familiarity; for familiarity, like slowly settling dust, gradually masks everything under a uniform, uninteresting gray. The child has the advantage of us, for to him everything is wonderful because everything is new."

"There have been those who have not lost this per-

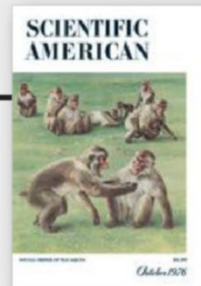
spective. Newton did not, as the story of the falling apple bears witness. [Alfred, Lord] Tennyson, although not professedly a scientific man, showed us that the scientist and the poet are blood brothers when he said of the flower in the crannied wall: '... if I could understand/ What you are/root and all/ and all in all/I should know what God and man is.'"

MOTORDOM GUINEA PIGS

"No one would think of the automobile racetrack as a practical laboratory, yet that is what it has become. Primarily the race is a test of the engineers, the people whose ideas are being tried out. It will tell each whether their years of research and labor have been worthwhile, or whether there have already been later developments which will render them useless. As such, no one watches the races with keener interest than these engineers. They are all at the race, for some brain-child of theirs is 'strutting its stuff' before the automotive world."

SOLID ROCK EXCAVATION

"Within a few months, the new tenants of offices in



the 45th story of the New York Life Insurance Building will have an unrivaled view of a metropolitan panorama. This they will see from directly above the place where once stood the exquisite figure of Diana that dominated the Madison Square Garden Building. This historical structure has been ruthlessly demolished, and great quantities of the ground beneath its foundation have been removed to make way for the substructure extending four stories below street level, of the new skyscraper.

"This involved the excavation of nearly 150,000 cubic yards of earth and stone from a pit 72 feet deep. Its safe and rapid excavation without injury or danger to life or property was a worthy engineering feat."

MOST REMARKABLE FISH DINNER

1876

"The fish culturists showcasing their breeding and other aquatic breakthroughs at the Centennial Exposition in Philadelphia treated

themselves to an extraordinary fish dinner. The bill of fare embraced 58 kinds of fish. Under the head of hors d'oeuvres we find Norwegian pluck fish, Portuguese conger eel, Spanish conger eel with tomatoes, Turkish botargoes or mullet roes, Japanese shake or dried salmon, crayfish from the Cape of Good Hope, French tunny fish, and, most astonishing, 'desiccated octopus eggs.'

"Noted scientists are honored by having their names applied to the various sauces, such as bisque of lobster, Seth Green style. One particular dish puzzled even the most ingenious chefs, and that was kanten (Japanese seaweed) à la Sekizawa Akekio [a pioneer in agriculture and fisheries]."

INFUSORIAL EARTH

"It is one of the paradoxes of nature that the smallest creatures contribute most to the structure of the earth. The higher forms of life are barely traceable in the rocky strata; the lowest make up the bulk of vast formations, thousands of miles in area, thousands of feet in depth. The gigantic labors of the minute but multitudinous coral polyps are proverbial. But these are surpassed by the remains of still more microscopic creatures [or microplankton] which swarm in all waters, and whose cast-off shells fall like a ceaseless rain of solid matter on every part of the ocean's bed."



1976, Social Order of Macaques: "Researchers observed a so-called subleader policing episode in a group of macaques. The episode, which lasted 1.5 seconds, starts with Tulip, a juvenile female, threatening Infinity, an adult female, shown here in an illustration based on a series of photographs."

Swiss Innovations and Alpine Inspirations

Delve into some of the world's most influential and innovative scientific advancements at places such as CERN and the Swiss Plasma Center, guided by Staff Reporter Joseph Howlett.

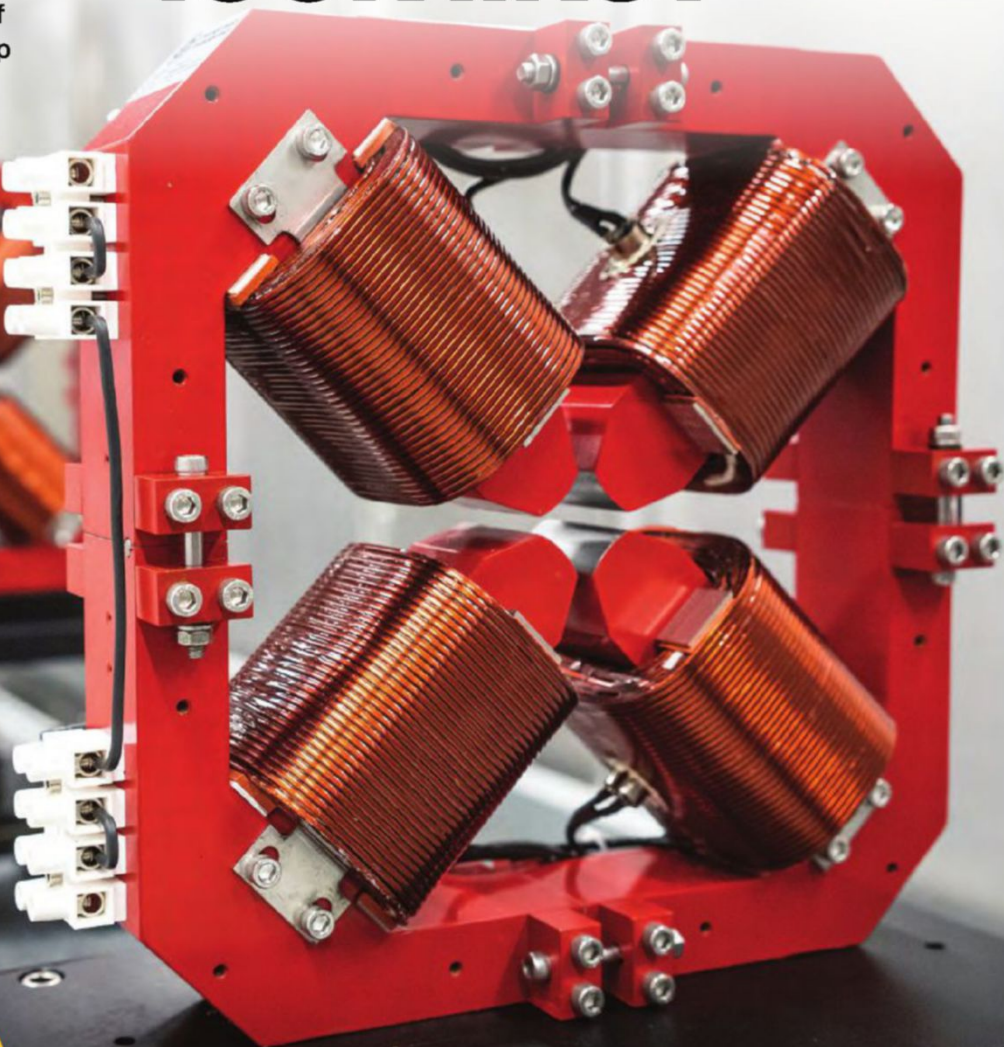
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Lucerne | Mount Pilatus



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The ASU logo, consisting of the letters "ASU" in a bold, purple font with a stylized sunburst graphic behind the "S".

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ASU ahead of MIT and Stanford — U.S. News & World Report, 11 years, 2010–20

