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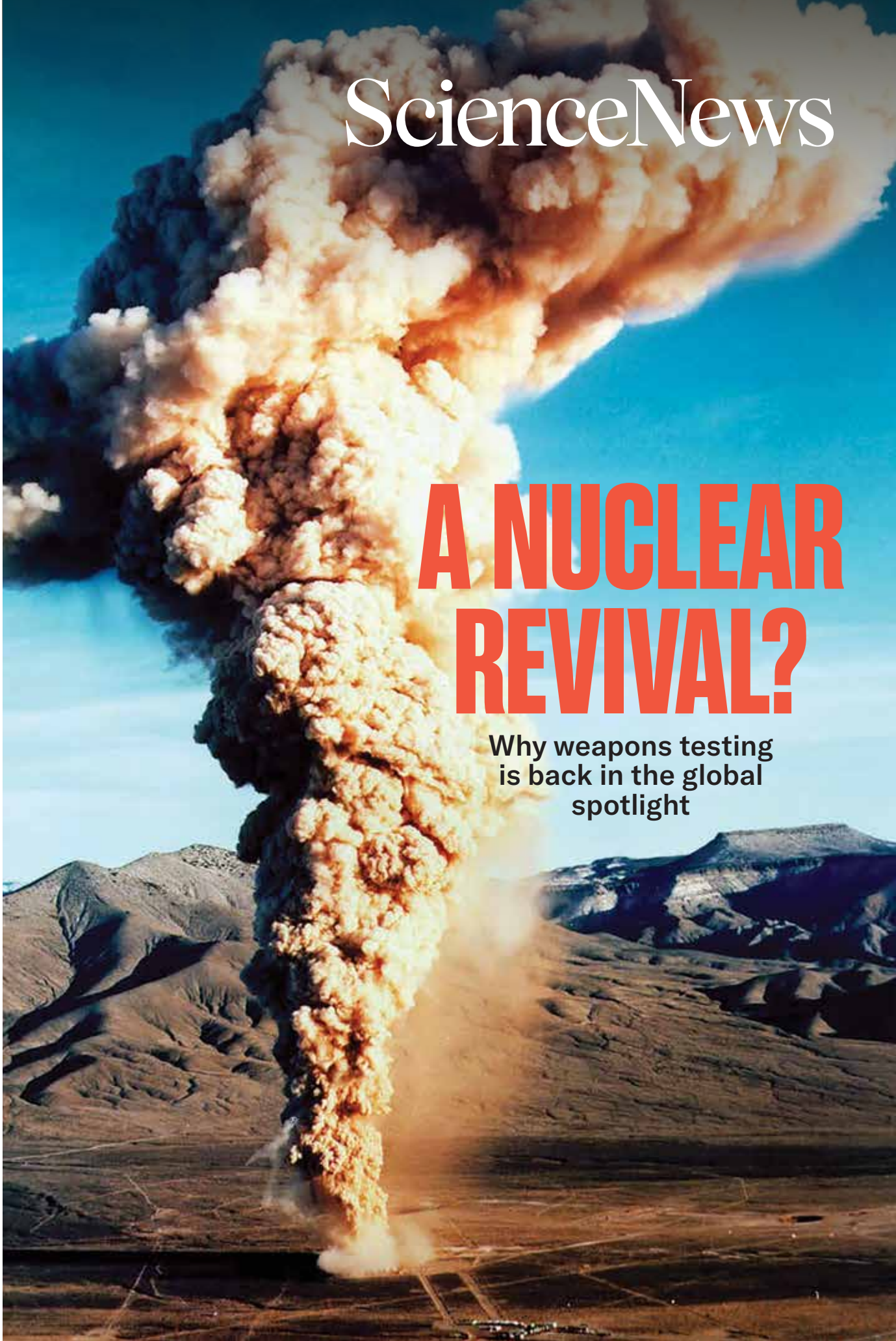

A NUCLEAR REVIVAL?

Why weapons testing is back in the global spotlight

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VOL. 207 NO. 4

APRIL 2025

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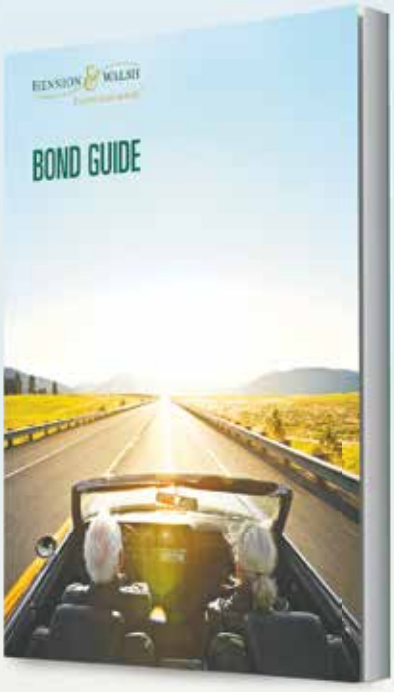

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News

On the Cover

Underground nuclear tests can accidentally release radioactive fallout, as in the 1970 Baneberry test (shown). PHOTO COURTESY OF THE NATIONAL NUCLEAR SECURITY ADMINISTRATION

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ALEX WILLIAMSON; GLENN HARVEY

A new era of testing nukes?

Science News has been covering nuclear physics since our earliest incarnation, starting with scientists' effort to decode the secrets of the atom. In the 1930s, readers learned about the discovery of the positron and scientists' first splitting of a uranium atom. The first sustained nuclear reaction followed soon after, in a repurposed squash court at the University of Chicago in 1942.

By then, what had once been a pursuit of basic knowledge had become a desperate wartime race to develop a nuclear weapon. The United States won that race. In 1945, U.S. forces dropped two atomic bombs on Japan that destroyed the cities of Hiroshima and Nagasaki, hastening the end of World War II.

In the 80 years since, no other nuclear bomb has been used as a weapon, though thousands of devices have been developed for testing. And while tests by the United States and other countries continued after the war, most countries halted these tests in the 1990s, around the time of the Comprehensive Nuclear-Test-Ban Treaty.

I confess that over the last 30 years, I have not spent much time ruminating on the threat of nuclear Armageddon. That changed for me in 2022, when Russia invaded Ukraine. Russian President Vladimir Putin lowered the threshold for a nuclear strike and reminded the world of the power of nuclear weapons to intimidate adversaries.

Fortunately, senior physics writer Emily Conover has been keeping watch on the science of nuclear weaponry and the geopolitical forces that affect it. A particle physicist turned journalist, Conover has a deep understanding of how the weapons work. In this issue, she explains the science of weapons testing (Page 32). Today, nuclear bombs are no longer being blown up in the Nevada desert. Instead, scientists are using "subcritical" nuclear experiments and computer simulations to gauge whether the weapons in the U.S. stockpile are still functional.

Conover also explains the renewed interest in the United States and elsewhere in reviving explosive tests. Physicists are divided on whether detonations are helpful to know if the bombs will work, Conover told me: "We have extremely good computer models of these weapons, but there could always be something we've missed."

It's unsettling to know that nuclear weapons testing may be back soon. But if even very limited knowledge is power, I'm glad to know the state of the science in a world that feels more unstable by the day.

Nancy Shute
Editor in Chief
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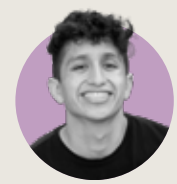
EMILY CONOVER

SENIOR PHYSICS WRITER

● EMILY CONOVER WAS IN THIRD GRADE the last time the United States tested a nuclear weapon. So when experts started telling her that the country might resume testing, she was both startled and curious about what testing would mean. "I wanted to better understand ... whether there might be a scientific justification for such a decision," Conover says. Her investigation resulted in this issue's cover story (Page 32). While reporting for the story at the Nuclear Deterrence Summit in Arlington, Va., Conover was struck by attendees' wholehearted belief in the idea that the United States needs nuclear weapons to deter other nations from using theirs. "The relationship most people have with nuclear weapons — fear, dread, uneasiness — wasn't apparent. It was a collegial affair with breaks for cookies, yet we were gathered to talk about the most deadly serious topic imaginable."

Tina Hesman Saey
Biological sex cannot be defined simply by reproductive cells. But the new Trump administration has asserted that there are only two sexes, defined by whether a person makes eggs or sperm. This "ignores intersex people whose biology doesn't develop along typical male-female lines," putting their lives, health and legal status in jeopardy, says senior molecular biology writer Tina Hesman Saey. In this issue, she explores the complex landscape of biological sex (Page 42).

Alka Tripathy-Lang
Some airlines offer passengers the option to spend a few bucks to offset carbon emissions from flying. Freelance science writer Alka Tripathy-Lang wondered what that funds. So she dug into the complicated world of carbon credits (Page 48). Despite an imperfect system, Tripathy-Lang plans to buy credits to show airlines that climate change matters. "It's not on me or any individual to single-handedly solve the world's environmental issues, but doing something feels better than doing nothing."



Alex Viveros
Reporting on how the Little Ice Age affected daily life in 16th century Transylvania gave Alex Viveros a rare opportunity to cover history (Page 28). It also revived the *Science News* intern's enthusiasm for the 2024 film *Nosferatu*, about a vampire "who is from this region of the world at approximately this period," Viveros says. "I was excited to learn about how people in Transylvania really experienced life 500 years ago."

McKenzie Prillaman
Arachnophobes be warned:
Within these pages is a photo of a cave spider covered in a whitish fungus. The newfound fungus devours the internal organs of its spider host, journalist McKenzie Prillaman reports (Page 26). Scientists named the fungus after broadcaster and naturalist Sir David Attenborough, and Prillaman attempted to reach him for comment. "But I had no luck in finding a way to get in contact other than snail mail," Prillaman says, which wasn't an option given her deadline.

CLOCKWISE FROM TOP LEFT: SOCIETY FOR SCIENCE (TOP TWO); ANNELISE JENSEN; COURTESY OF A. VIVEROS; SARAH TRAN

ANIMALS

AN AVIAN GLOW-UP

By Susan Milius

● With their flashy feathers and fancy moves, birds of paradise are known for their extravagant looks. But a trick that boosts that zing has been overlooked. Under the right light, natural biofluorescence can intensify the birds' colors. In the first survey of biofluorescence for these showy birds, researchers report in *Royal Society Open Science* that 37 of the 45 known species naturally fluoresce. In the specimen from the American Museum of Natural History shown here (*Paradisaea guilielmi*), the back (this page) and the underside (opposite) absorb blue light and emit more of a yellow hue. Bird of paradise males wow females using a plethora of bling, so the ability to intensify their color through biofluorescence fits right in. While the extra dazzle falls within the range of human vision, it isn't noticeable in normal daylight. But in the dense forests where these birds live, blue and ultraviolet filtering through the canopy may amplify the fluorescence. PHOTO BY RENE MARTIN

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Finally After 20 Years We Are Offering a Limited Release of the "Only Watch"

A few decades ago, when I first began my journey into watchmaking, I asked my top watchmaker to create something truly special just for me—a timepiece that embodied timeless elegance. The result was a masterpiece: a three-eye chronograph with a date display, a sun and moon indicator, a beautifully detailed guilloché dial, and raised Roman numeral hour markers.

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—Mike Bisceglia, Founder, Stauer

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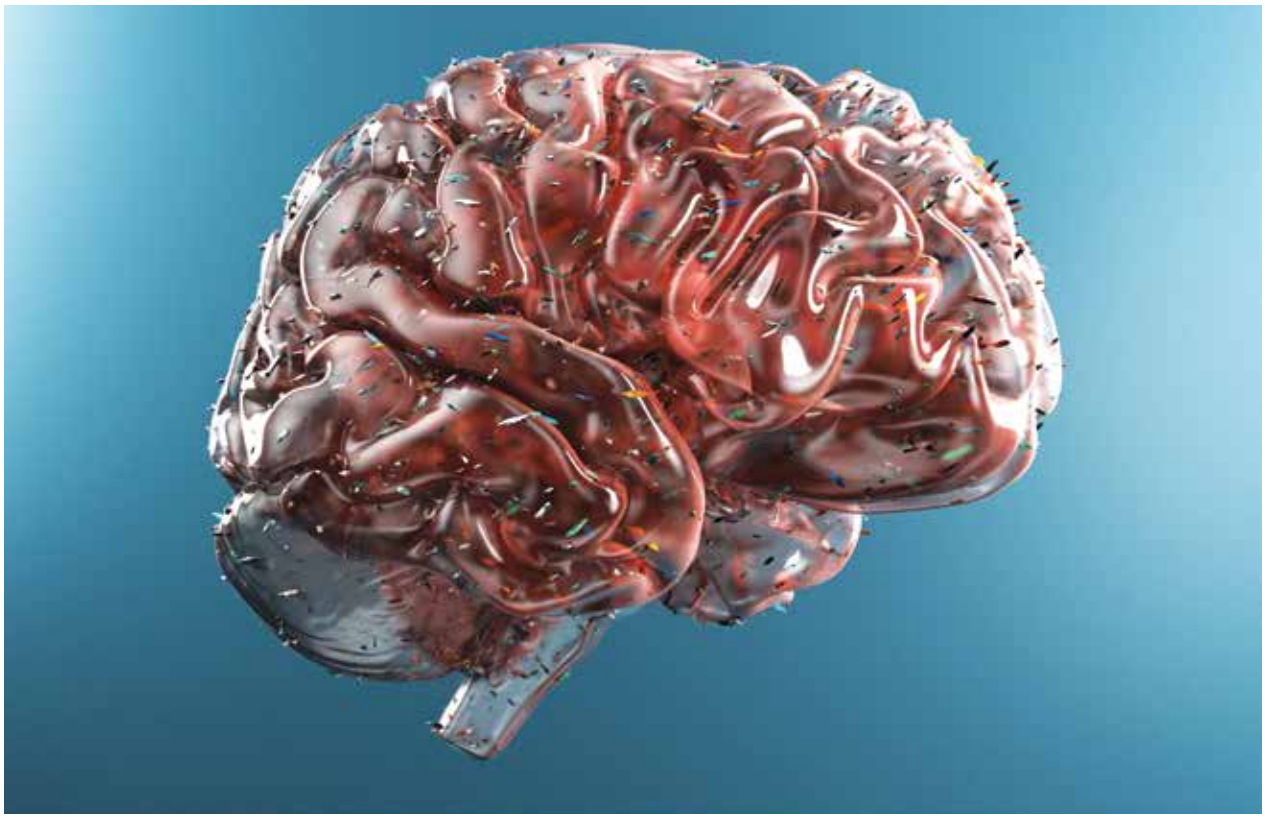
News

MONTSERRAT CAPELLADES, ALEJANDRO ALONSO-DÍAZ AND ÁNGEL SÁNCHEZ/CRAG

PLANTS

PLANT GOT A BOO-BOO? TRY A 'BAND-AID'

● Patches made from bacteria-produced cellulose can boost botanical healing. Scientists applied the patches to cut leaves of the plants *Nicotiana benthamiana* and *Arabidopsis thaliana.* After a week, over 80 percent of treated cuts had healed compared with less than 20 percent of untreated ones. Adding a patch to a bit of plant in a lab dish made roots sprout faster than control snippings (shown above). The bacteria, which coevolved with plants, probably infuse the cellulose with beneficial hormones, the researchers report in *Science Advances*. — *Javier Barbuzano*



HEALTH & MEDICINE

Plastic shards permeate human brains

By Laura Sanders

● **Our brains are increasingly plastic.** Minuscule shards and flakes of polymers are surprisingly abundant in brain tissue, a study of postmortem brains shows.

This appraisal of microplastics and nanoplastics, published in *Nature Medicine*, raises questions and worries about what this plastic is doing to us.

"The findings are both significant and concerning," says Raffaele Marfella, a cardiovascular researcher at University of Campania "Luigi Vanvitelli" in Naples, Italy. Marfella and colleagues recently found that people with micro- and nanoplastics, or MNPs for short, in blood vessel plaques were at higher risk of heart attacks, strokes and death.

Plastic levels are tricky to measure. To get the full picture, researchers used several different methods to measure MNPs in 91 brain samples collected from people who died as far back as 1997. The measurements all pointed to substantial increases over the years. From 2016 to 2024, the median concentration of MNPs increased by about 50 percent, from 3,345 micrograms per gram to 4,917 micrograms per gram — roughly three bottle caps worth of plastic.

"The levels of plastic being detected in the brain are almost unbelievable," says study coauthor Andrew West, a neuroscientist at Duke University. "In fact, I didn't believe it until I saw all the data" from multiple tests with different samples.

HITANDRUN

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Unbelievable, but not surprising, given how plastic has permeated the world. "Microplastics are in the food we eat, the water we drink and even the air we breathe," says Richard Thompson, a microplastic pollution expert at the University of Plymouth in England who helped discover microplastics. Of course they've made their way into human tissue, he says. Previous studies have found them in lungs, intestines, blood, livers and placentas.

In the samples collected in 2024, concentrations of MNPs in brain tissue were about 10 times the levels in liver and kidney tissue, the researchers report. Scientists had wondered if the blood-brain barrier, a cellular do-not-pass zone, could keep these polymers out. That doesn't seem to be the case.

"This study clearly demonstrates that they are there and in high concentrations," says Phoebe Stapleton, a toxicologist at Rutgers University in Piscataway, N.J. "The next steps will be to understand what they are doing [in the brain] and how the body responds to them."

In addition to the levels of MNPs described, their shapes are unexpected, Stapleton says. Thin, sharp particles — not solid grains — were present in the brain tissue.

Many lab-based health studies of MNPs experiment with engineered beads of polystyrene, a plastic used in the food industry, medical supplies and more. But the brains didn't have much polystyrene; there was, however, abundant polyethylene — a plastic used in grocery bags, shampoo bottles, toys and other household goods. The aged shards in the brain "look like nothing we have used yet in the lab," West says, suggesting that the lab data might not be so relevant to what's happening in human brains. CONT. ON PAGE 14

HEALTH & MEDICINE

A BLOOD TEST CAN SPOT EARLY SIGNS OF PANCREATIC CANCER

BY MEGHAN ROSEN

Just one drop of blood could someday reveal if you have pancreatic cancer.

A prototype test called PAC-MANN can detect signs of the disease in people's blood, even at an early stage, researchers report in *Science Translational Medicine*. It could one day give doctors a simple way to catch the disease before it's too late for treatment.

"There's really a desperate need in the field for an early detection test for pancreatic cancer," says molecular biologist Jared Fischer of Oregon Health & Science University in Portland. Though somewhat rare, pancreatic cancer is one of the most lethal cancers, responsible for more than 50,000 deaths in the United States in 2024. Patients are often diagnosed late in the cancer's progression, because the disease can be so difficult to spot.

Unlike what's available for other diseases, doctors don't have anything that can easily reveal early cases of pancreatic cancer. They're mostly limited to biopsies and imaging tests. But pancreatic cancer does have some molecular red flags, which Fischer and biomedical engineer Jose Montoya Mira, also of Oregon Health & Science University, tapped into with PAC-MANN. Like the ghost-gobbling hero of the classic arcade game, some pancreatic cancer proteins are known for their ability to chomp. These proteins, called proteases, break down connective tissues, giving tumors space to grow.

The pair built PAC-MANN, or Protease-ACtivated MAgnetic NaNosensor, to detect chomping proteins found in pancreatic cancer. The nanosensor is made of a magnetic bead linked to fluorescent molecules. When mixed with blood from a pancreatic cancer patient, proteases cleave the fluorescent molecules from the bead, releasing them into solution. Using a magnet, the team pulls any remaining nanosensors away. Left behind are the cleaved fluorescent bits, which glow under visible light.

Added to blood samples from 178 people who either didn't have pancreatic cancer or had already been diagnosed with early, middle or late-stage disease, PAC-MANN correctly detected whether participants had cancer 90 percent of the time. It ID'd 40 out of 55 people with the disease and 120 out of 123 people without. The team is now planning to start a clinical trial. ✖

CONT. FROM PAGE 13 Higher MNP levels appeared in 12 brains of people with dementia diagnoses. That result can't say anything about whether one caused the other. Brain changes that come with dementia could allow more plastic to enter.

Plastic loads weren't linked to age at death, suggesting that accumulation over the years isn't a given. Scientists want to study why some people have high levels while others seemingly avoid buildup, West says.

The results come with caveats. The sample sizes were relatively small. Contamination risks and variability in measurements can make interpretation hard. And the study didn't follow plastic levels in living people, so it's not known if or how MNPs might fluctuate over time.

Big questions remain, including how MNPs get into the brain, whether they can be removed and — perhaps most pressing — if they are harmful or benign.

"We do not know the health implications of microplastics in the brain," West says. But it would be a mistake to wait to get all the answers before addressing the issue, he adds. "People are wondering, 'Is this the next asbestos, or the next lead, or is it even something much worse than what we've seen — harder to detect and harder to get rid of?'" ✖

"The levels of plastic being detected in the brain are almost unbelievable."

— Andrew West

PHYSICS

The best way to cook an egg — in 32 minutes

By Bethany Brookshire

● **When egg prices are hard-boiling your temper,** it's important to make sure that each egg you make is the best it can possibly be. But when your egg white is cooked, your egg yolk is often still a runny mess. Once the yolk is cooked, the white is rubbery. The solution is a method called periodic cooking, researchers report in *Communications Engineering*. And true eggcellence, they say, requires only a few ingredients: boiling water, slightly warm water, an egg — and 32 minutes of patience.

The challenge of cooking an egg is that the yolk and the white, or albumen, have different compositions, says chemical engineer Emilia Di Lorenzo of the University of Naples Federico II in Italy. The result is that the proteins in each part of the egg come apart at different temperatures. Yolk proteins cook at 65° Celsius, while those in the white cook at 85°.

The challenge of heating two parts of a single item at different temperatures appealed to Ernesto Di Maio, a materials scientist also at the University of Naples Federico II. His lab studies varying boundary conditions — changing temperatures, pressures or other conditions to create two different internal processes in materials such as plastics.

But then, a colleague told him, "'You know, there is a cook in Italy which sells his single egg for 80 euros,'" Di Maio recalls. "This cook separates the egg and the yolk, cooks them at two different temperatures — the optimal one[s] — and then puts them together again in a fancy way with the other ingredients." When Di Maio learned of the pricey dish, "it was really obvious to me to try what we know about plastic forms out on the egg."

Di Lorenzo, Di Maio and colleagues ran mathematical and computational models of the heat transfer inside the egg white and yolk and simulated how different cooking times and temperatures affected the inner materials. They found that periodic cooking, varying the temperature back and forth between 100° and 30°, allowed the yolk and white to reach different temperatures at different times.

"When you change a boundary condition, the heat will reverse, so the heat flow will go from positive to negative and vice versa," Di Maio says. "After a few cycles, you end up with a stationary solution of this problem, which gives a rather

Scientists compared the chemical structures and textures of raw, hard-boiled, soft-boiled, sous vide and periodically cooked eggs. The periodic cooking method resulted in an egg with a white like a soft-boiled egg, but a yolk more like a sous vide. ↓

Raw

Hard-boiled

Soft-boiled

Sous vide

Periodic

PELLEGRINO MUSTO AND E. DI MAIO

constant temperature for the yolk, and temperature which goes from 30° to 100° for the albumen."

The team then began cooking real eggs, comparing periodically cooked eggs with raw, hard-boiled, soft-boiled and sous vide varieties. Di Lorenzo and colleagues analyzed the results with spectroscopy and tests for hardness, chewiness and gumminess. A panel of eight sensory experts measured flavor, odor, wetness and more. The periodic egg had a white that was comparable to that of a soft-boiled egg, but a yolk most similar to a sous vide egg.

Here's the final recipe: Prepare a pot of boiling water, and a pot of water at 30°. Put the egg in the boiling water for two minutes, then transfer it to the 30° pot for two minutes. Repeat the process eight times, for a total of 32 minutes.

"It's very refreshing to see people taking food this seriously," says César Vega, a food scientist at McCain Foods in Chicago. "It left me thinking, what are the implications of the technique in the world of food?"

But not everyone is so eggcited. While Di Lorenzo found the study fascinating, she was grateful to outsource the taste test. "Eggs are not my favorite thing in the world, but I ate it once," she says. "I had to do it for science." ✖

HOW TO COOK THE PERFECT EGG

1. Prepare one pot of boiling water and one pot of water at 30° Celsius.
2. Boil the egg for two minutes, then transfer it to the 30° pot for two minutes.
3. Repeat the process eight times, for a total of 32 minutes.

HEALTH & MEDICINE

WHY SCRATCHING IS BOTH GOOD AND BAD

By Laura Sanders

● Scratching an itch can bring both pleasure and misery. A mouse study on scratching, reported in *Science*, fleshes out this head-scratching paradox and could point out ways to better curb pernicious itch in people.

First, the bad news: Scratching itchy ears led to a round of inflammation. Itch-provoking substances, such as the oil in poison ivy, activate mast cells, immune sentries that release itch signals and kick off inflammation. But so does scratching, the new study suggests. "The act of scratching is actually triggering the inflammation by synergizing with mast cells to make them more effective," says Daniel Kaplan, a dermatologist and immunologist at the University of Pittsburgh.

Mice that couldn't scratch their itchy ears, thanks to tiny cones of shame, had less inflammation than mice that scratched. The same was true for mice that didn't sense the itch, the scientists report. Kaplan relates the results to a mosquito bite. "Most of the time, it'll go away in five, 10 minutes," he says. "But if you start scratching it, now, you get a really big, inflamed, itchy lesion ... that can stick around for several days. It's a lot worse. And I think this could be a mechanism that explains why."

Now the good news: Scratching lessened the amount of potentially harmful bacteria on mice's skin, perhaps through the heightened immune reaction it prompts. "That was a clear demonstration that scratching can have a benefit in the context of an acute infection," Kaplan says. But too much scratching can rip the skin and usher in more bacteria, he cautions. "In that sense, scratching, through a different mechanism, also makes things even worse."

In recent years, scientists have uncovered new details about itch and developed new ways to fight chronic forms of it, Kaplan says. The new study may point out other approaches for treatments.

So, bottom line, is scratching good or bad? "It's both!" Kaplan says. ✖

THE HEALTH CHECKUP

THE VAGINA'S MICROBES NEED MORE ATTENTION

BY MCKENZIE PRILLAMAN

Science is notorious for overlooking the female body. And perhaps the most taboo part is the vagina. This reproductive organ is home to billions of bacteria, archaea, fungi and viruses. Yet for how crucial the vaginal microbiota are to half the population's health, there's a dearth of data on these microbes and their functions in the body. To remedy the situation, a group of researchers is turning to citizen scientists to crowdsource that data.

A few years ago, microbiologist Sarah Lebeer of the University of Antwerp in Belgium and colleagues launched the Isala project (named after Belgium's first female doctor). Women can volunteer online for a variety of ongoing studies on the vaginal microbiome. Many selected participants receive sample collection kits that they return by mail. Scientists in around 10 more countries are now starting their own regional projects as part of the Isala Sisterhood consortium.

"If we better understand when a vaginal microbiome is disrupted and how it can cause disease, then we can have better diagnostic tools ... and can think of new therapies," Lebeer says.

Already, the project has pointed to potential flaws in how scientists have been studying the vaginal microbiome. Previous research identified some 20 categories of vaginal bacterial communities, defined by the dominant species. But Lebeer's work suggests that the categories are too limited and that categorizing bacterial community types misses the forest for the trees. More than 10 percent of 3,345 women in Belgium had a microbial composition that sat in between previously defined categories and could not easily be sorted, Lebeer and colleagues reported in *Nature Microbiology*.

Internationally, vaginal microbiota are "even more diverse," Lebeer says. Many factors, from diet and hormone levels to hygiene practices and experiences with childbirth, can influence the vagina's microbial makeup.

Due to this diversity and advanced computing power, researchers should go beyond categories and instead consider microbiota compositions as a spectrum, Lebeer and colleagues contend in *Trends in Microbiology*.

A whole-composition approach could help physicians easily identify healthy microbiota and look out for communities that are out of balance, Lebeer says. For instance, a reduction of *Lactobacillus* species and an overgrowth of other bacteria — a condition called bacterial vaginosis, or BV — has been associated with urinary tract infections, inflamed uterine linings, preterm birth and reduced HIV drug efficacy.

Doctors typically treat the condition with one of two antibiotics. But more options are needed. A previous study found that within a year of treatment, BV came back in nearly 60 percent of women. At any given time, about 26 percent of reproductive-age women globally have the condition, the World Health Organization reports.

Genomicist Jacques Ravel of the University of Maryland School of Medicine in Baltimore applauds the team's call for more research. But he doesn't think surveys are the way to develop better prevention and treatment methods for health issues like BV. Instead, he wants to know how, exactly, these microbes help or harm health. This kind of research will require people to come into a lab or clinic to provide samples that will be analyzed right away, he says.

But Lebeer argues a better understanding of well-balanced vaginal microbiota can be fruitful too. For instance, scientists have started studying vaginal transplants of *Lactobacillus* as a potential BV treatment.

Citizen science can also drive research in new directions. Lebeer's project on how menstrual hygiene products affect vaginal microbes was proposed by people engaging with the Isala project. "If you do citizen science," she says, "you have more experts around the table." ✖

SARAH TRAN

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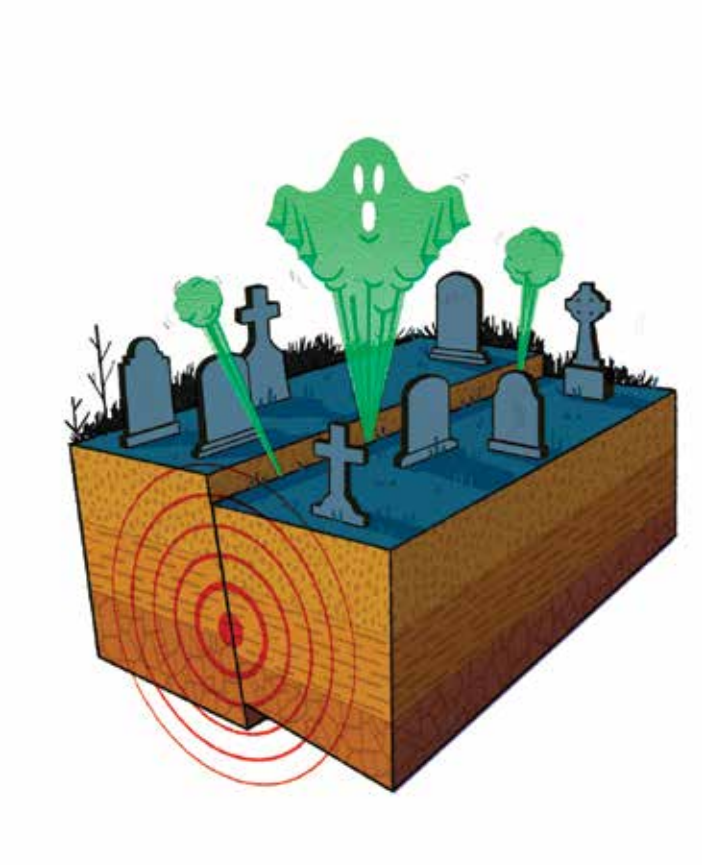


EARTH

Spooky lights could be earthquake farts

By Nikk Ogasa

● **A South Carolina ghost story** could have a very earthly explanation.

Starting in the 1950s, folks in the Summerville, S.C., area began reporting sightings of strange balls of light floating down a remote road near some abandoned railroad tracks. Local lore has it that the eerie illuminations, known as the Summerville Light, are the glow of a lantern carried by a forlorn ghost.

But perhaps earthquakes are the source of this phantom light, and of some other ghostly legends too, geologist Susan Hough proposes in *Seismological Research Letters*. Radon, methane or other gases that rise from the ground during quakes could have been ignited by static electricity or sparks from shifting rocks, causing the vapors to luminesce, suggests Hough, of the U.S. Geological Survey in Pasadena, Calif.

Located far from any tectonic plate boundaries, Summerville might seem an unlikely spot for quakes. But in 1886, a temblor of around magnitude 7 devastated the nearby city of Charleston, killing 60 people. That event and hundreds of aftershocks over the following decades revealed the area's pronounced seismic hazard.

The region is rich in ghost tales too, the most famous of which may be the Legend of the Summerville Light. The story generally goes that one night, a railroad worker's wife was waiting for him by some tracks when she learned that he was decapitated in an accident. From then on, and even after her death, the woman returns to the tracks each night, carrying a lantern as she searches for her husband's head.

Curious if the light could be explained by a physical mechanism, Hough reviewed books, magazines and online sources for recorded sightings of the mysterious orbs and other supernatural claims from the area. She also studied the area's earthquake history from 1890 to 1960 — the period leading up to and including the start of the sightings.

Only a few quakes were documented during that time span: a magnitude 3.9 in 1907 and a magnitude 4.4 in 1959 — around when the sightings began. A couple of smaller quakes followed shortly thereafter, in 1960. These earthquakes probably would have been accompanied by additional, even

↖ **Reported ghost sightings in South Carolina may have been due to earthquakes. Temblors around the time of the sightings could have released gases that ignited into balls of light.**

PETE RYAN

smaller quakes that went undetected, Hough says. Despite the temblors' small size, they could have generated a phenomenon known as earthquake lights without anyone suspecting a quake had occurred.

Other instances of supernatural activity reported in the area, such as cars shaking violently, objects and doors moving spontaneously and footsteps heard in upstairs rooms could also be explained by inconspicuous earthquakes.

Many of the reports seem to fit with shaking known to occur at a II on the Modified Mercalli Intensity scale, which scientists use to rate quakes based on inflicted damage and witnesses' perceptions, Hough says. Shaking intensity is generally considered to be at a II if it is weak and "felt only by a few persons at rest, especially on upper floors of buildings."

Hough's proposal is reasonable, says earthquake scientist Yuji Enomoto of Shinshu University in Matsumoto, Japan. But more data are needed to clarify which natural mechanism could be behind the Summerville Light.

The most helpful, Enomoto says, would be "data on the presence of an anaerobic environment containing organic matter capable of generating methane, and the existence of granitic bedrock containing radium, which can produce radon."

For Hough, one of the more intriguing implications of the work is the possibility that similar ghost stories elsewhere could be associated with subtle seismic activity.

"There's a bunch of ghosts wandering the rails in different places in the United States ... carrying lanterns looking for severed heads," Hough says. "Maybe they are illuminating shallow active faults." ✖

PLANETARY SCIENCE

THE MOON'S GRAND CANYONS FORMED IN MINUTES

BY LISA GROSSMAN

A giant impact 3.8 billion years ago sent a curtain of rock flying away from a point near the moon's south pole. When that curtain fell, its rocks plunged as deep as 3.5 kilometers into the lunar surface with energies 130 times that of the global inventory of nuclear weapons, new calculations show.

And that's how a hailstorm of boulders carved out two gargantuan canyons on the moon in less than 10 minutes, researchers report in *Nature Communications*.

"They landed in a staccato fashion, bang-bang-bang-bang-bang," says planetary geologist David Kring of the Lunar and Planetary Institute in Houston.

The two channels, Vallis Schrödinger and Vallis Planck, extend in straight lines from the 320-kilometer-wide Schrödinger basin marking the initial impact. Until now, the circumstances of the canyons' formation have been a mystery. The canyons are 270 and 280 kilometers long and up to 2.7 and 3.5 kilometers deep, respectively.

"The landscape of the south polar region of the moon is so dramatic," Kring says. "If it occurred on Earth, it would be a national or international park." The Grand Canyon, for example, winds for a sinuous 446 kilometers and is only about 1.8 kilometers deep at its deepest point.

The south pole also contains some of the oldest rocks on the moon, perhaps dating back to the moon's formation roughly 4 billion years ago. Collecting samples from there would let scientists test some of the biggest mysteries about the moon's history. That is one of the goals of NASA's Artemis missions, which aim to land astronauts on the moon in 2027.

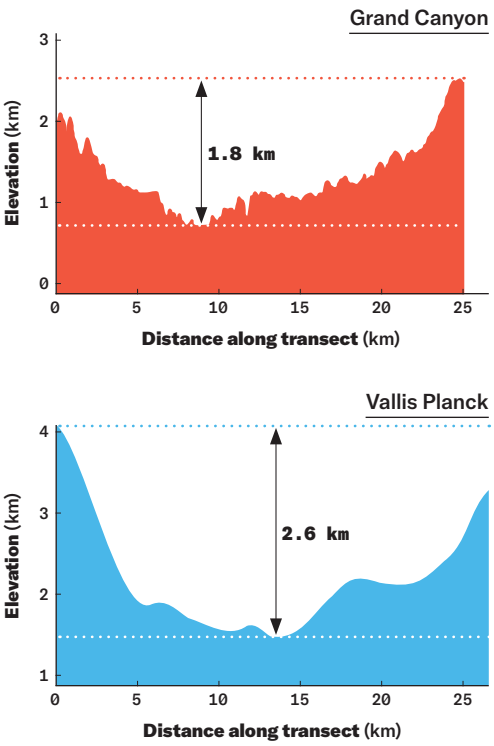
But there's a potential barrier to collecting those rocks. The rim of the Schrödinger basin is about 125 kilometers from the astronauts' anticipated landing site. Scientists worry that the basin-forming impact splashed debris in all directions, possibly burying those tantalizing older rocks.

To see if that's the case, Kring, together with geologists Danielle Kallenborn and Gareth Collins of Imperial College London, analyzed spacecraft images of the Schrödinger basin and its canyons to deduce the physics of CONT. ON PAGE 20

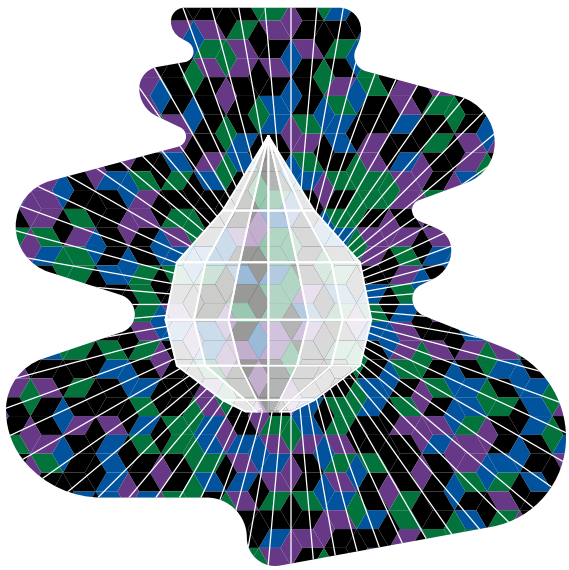
CONT. FROM PAGE 19 their formations. The canyons' origins were swift and explosive, the team found, and the straight lines converge toward Schrödinger basin's southern edge rather than its middle. The convergence suggests the impactor came in toward the moon at an angle, and splashed material northward, away from the Artemis exploration zone.

That finding "means that very little of the Schrödinger material is going to be burying this very old terrain," Kring says. "We have an opportunity to peer deeper into lunar history and better understand the earliest epoch of the Earth-moon system." ✖

A TALE OF TWO CANYONS



Compared with the Grand Canyon (as measured along the Bright Angel hiking trail, top), Vallis Planck on the moon's south pole (bottom) is wider and deeper.



FROM LEFT: D.A. KRING *ET AL/NATURE COMMUNICATIONS* 2025, ADAPTED BY B. PRICE; GREG MABLY

PHYSICS

Physicists create a weird ice that may exist on exoplanets

By Nikk Ogasa

● **A strange type of ice** thought to dwell deep in the oceans of alien worlds has finally been proved to exist.

For the first time, researchers have directly observed a sort of hybrid phase of water called plastic ice, which forms at high temperatures and pressures and exhibits traits of both solid ice and liquid water. The observations, reported in *Nature*, may help scientists better understand the internal architecture and processes of other worlds, some of which might be habitable.

Plastic ice is "something intermediate between a liquid and a crystal, you can imagine that it is softer when you squeeze it," says physicist Livia Bove of CNRS in Paris. It's called plastic ice because it is more malleable than typical crystalline ice, exhibiting a property called plasticity, she says. "Like something that can [squeeze] through a hole and come out, even if it's still solid."

Most of the ice on Earth's surface — including ice cubes, glaciers and snow — consists of water molecules arranged in a hexagonal lattice that resembles a honeycomb. Scientists classify this common ice as ice Ih. In addition to ice Ih, there are at least 20 other known ice phases that form in different pressure and temperature conditions.

At pressures above roughly 20,000 bars, or nearly 20,000 times Earth's atmospheric pressure at sea level, ice lattices compress into ice VII. This form of ice is a polymorph with a dense, cubic structure in which molecules are ordered like the cubies in a Rubik's Cube. Ice VII has been found trapped in diamonds originating from Earth's mantle and is thought to occur inside other planets too. And fans of Kurt Vonnegut, who created the terrifying ice-nine in his novel *Cat's Cradle*, may be interested to learn that an ice IX was discovered in 1996, though it lacks the ability to freeze entire oceans.

There are also ice phases that have only been theorized to exist. Over 15 years ago, computer simulations showed that when ice VII is heated and subjected to extreme pressures, its individual water molecules should start to rotate freely, as if a liquid, while occupying fixed positions, as in a solid. Since the hypothetical phase shared the same cubic crystal structure as ice VII, it became known as plastic ice VII. But because performing experiments at such high pressures was technically infeasible at the time, solid evidence of plastic ice's existence eluded scientists for years.

For the new study, Bove and colleagues used a relatively new tool that measures the motions of molecules under extreme pressures. In experiments, the team pointed a neutron beam at water samples, subjecting them to temperatures up to 326° Celsius and pressures up to 60,000 bars. As the neutrons interacted with the water molecules, they gained or lost energy depending on how much the molecules moved and rotated, before scattering away toward a detector. Measuring the scattered neutrons' energies allowed the scientists to characterize the water molecules' motions and identify the phase of ice that had formed.

Above 177° and over about 30,000 bars — roughly 28 times the pressure at the deepest point in Earth's oceans — the ice had a cubic crystal lattice with molecules that rotated about as fast as those in liquid water. The researchers identified the phase as plastic ice VII, confirming its existence.

But one observation diverged from predictions. Rather than revolving freely, the water molecules swiveled in jerky motions, breaking their hydrogen bonds with one neighbor only to rapidly turn and bond with another. This jumpy rotation may enhance the ice's thermal conductivity and elasticity.

Plastic ice VII may have existed during the early formational stages of Europa, Titan and other icy moons in our solar system, before all the water had escaped from their high-pressure interiors, says planetary scientist Baptiste Journaux of the University of Washington in Seattle. The new findings could help scientists piece together how these moons evolved into the ocean worlds they are today, he says.

Beyond our solar system, the strange ice may repose at the bottom of giant oceans on exoplanets, some of which are thousands of kilometers deep and might be habitable, Journaux says. Investigating how readily plastic ice VII adds salts to its lattice could help determine whether the phase's presence would enhance the exchange of nutrient-bearing salts between exoplanet seafloors and the oceans above, he says. "That would actually feed the ocean with more nutrients." ✖

The ice has a cubic crystal lattice with molecules that rotate about as fast as those in liquid water.

ASTRONOMY

ODD FLARE HAILED FROM A DEAD GALAXY

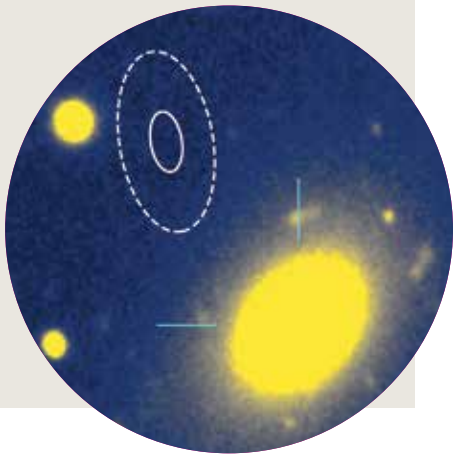
By Lisa Grossman

● A staccato blast of electromagnetic energy has been tracked to an old, dead galaxy for the first time. The discovery supports the idea that there is more than one way to produce such flares, called fast radio bursts, or FRBs.

Scientists have detected thousands of these intense radio-wave eruptions, but only about 100 have been traced to their origins, says astronomer Tarraneh Eftekhari of Northwestern University in Evanston, Ill. Most came from neighborhoods of young stars.

Over six months in 2024, the CHIME telescope in Canada detected 22 signals from a blast dubbed FRB 20240209A. Six of the signals let Eftekhari's team track the blast's location (a dotted ellipse in the telescope image below) to the outskirts of an ancient, dead galaxy (center marked with cross hairs), the scientists report in the *Astrophysical Journal Letters.*

Stellar corpses called magnetars, the magnetized remnants of supernova explosions, are thought to produce most FRBs. Such supernovas are expected where a lot of stars are forming, not in old, dead galaxies. But another peculiar FRB, detected in 2021 and traced to a ball of old stars called a globular cluster, hints that magnetars could form via neutron star smashups or a white dwarf collapsing under its own gravity. Eftekhari plans to search for a globular cluster in the spot the new FRB came from. ✖



PARTICLE PHYSICS

A COSMIC NEUTRINO SMASHES ENERGY RECORDS

BY MARIA TEMMING

A neutrino from space recently plunged into the Mediterranean Sea with an energy that blows all other known neutrinos out of the water.

Packing a punch of 220 million billion electron volts, this particle was around 20 times as energetic as the highest-energy cosmic neutrinos seen before, researchers report in *Nature*. The particle was glimpsed by the partially built Cubic Kilometre Neutrino Telescope, or KM3NeT.

Scientists are keen to catalog cosmic neutrinos because the lightweight, neutral particles can cross vast stretches of space nearly undisturbed. The most energetic ones could offer insights into the powerful phenomena that spit them out, such as supermassive black holes.

Though still under construction, KM3NeT's two neutrino detectors — one off the coast of Sicily, the other near southern France — are already collecting data. When cosmic neutrinos interact with matter in or near a KM3NeT detector, they spawn charged particles such as muons. As those muons careen through water, they give off feeble flashes of bluish light that KM3NeT's sensors can pick up. On February 13, 2023, an extremely energetic muon traveling nearly parallel to the horizon zipped through the detector near Sicily. The muon's energy and trajectory indicate that it was spawned by a neutrino from space rather than a particle from the atmosphere.

Data from gamma-ray, X-ray and radio telescopes narrowed the neutrino's probable origins to 12 objects. Most of them are supermassive black holes guzzling gas and dust, says KM3NeT team member Luigi Antonio Fusco, a physicist at the University of Salerno in Fisciano, Italy. "The problem is that there are so many, you cannot really pinpoint a single one," he says. Another possibility is that this is the first observed cosmogenic neutrino, created when ultrahigh energy cosmic rays mingle with photons from the afterglow of the Big Bang.

"At this point, it's very difficult to make conclusions about the origins," says theoretical physicist Kohta Murase of Penn State. The completion of KM3NeT and other neutrino telescopes around the world should help scientists home in on the birthplaces of high-energy neutrinos, he says. ✖

V. SHAH *ET AL*/*ASTROPHYSICAL JOURNAL LETTERS* 2025

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ANIMALS

HOW MANTIS SHRIMP SURVIVE THEIR OWN PUNISHING BLOWS

BY JAKE BUEHLER

Mantis shrimp, famous for their ultrafast punches, can land powerful volley after volley to their prey without major injury to their own nerves or flesh. That's because the exoskeleton of their clublike forelimbs filters out the most damaging pressure waves caused by a strike, researchers report.

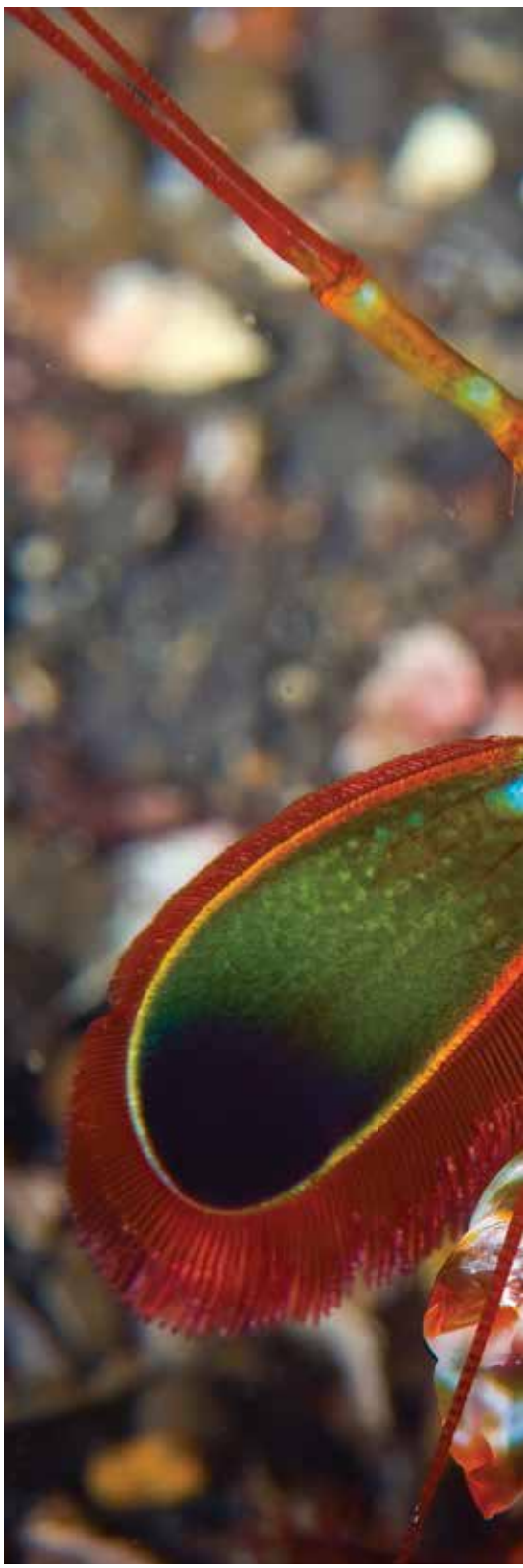
Though small enough to fit in your hand, peacock mantis shrimp (*Odontodactylus scyllarus*) strike so fast that they create imploding bubbles. The impact and implosions work in concert to inflict forces that can exceed 1,000 times the mantis shrimp's body weight.

Scientists thought the mantis shrimp's resilience to these blows might come from the architecture within the club's armor. Layers of mineral-hardened chitin — a long chain of sugars that is the primary component of the exoskeleton — rest above deeper stacks of chitin bundles. Those deeper layers are rotated slightly with respect to the layers above and below, much like a stack of paper that's been twisted, creating a helixlike corkscrewing shape.

In lab experiments, engineer Horacio Espinosa and colleagues tested how high-energy waves move through the club's architecture. The mineralized outer layers control the spread of tiny cracks from the strike impact itself, while the deeper helix-like layers dissipate or neutralize the highest-energy waves, the team reports in *Science*. That "prevents shear waves from damaging soft tissue within the club," says Espinosa, of Northwestern University in Evanston, Ill.

The exoskeleton architecture could inspire new materials. David Kisailus, a materials scientist at the University of California, Irvine, is already using the helix structure design to enhance the toughness of airplane wings and wind turbine blades. Kisailus studies other species with promise for inspiring high-performance materials.

He wagers the new findings are the tip of the iceberg: "I know that there are many, many blueprints out there just waiting to be revealed in nature's plethora of organisms." ✖



→ The peacock mantis shrimp has hammerlike weaponry (outer tan-and-white limbs, with orange clubs tucked underneath).

ANDREW THIRLWELL/MOMENT/GETTY IMAGES

VOL. 207 NO. 04 | APRIL 2025

ANIMALS

A CREEPY FUNGUS TURNS CAVE SPIDERS INTO ZOMBIES

By McKenzie Prillaman

● A newfound fungus transforms cave spiders into zombies, researchers report in *Fungal Systematics and Evolution*. Dubbed *Gibellula attenboroughii*, after the naturalist Sir David Attenborough, the fungus was first spotted on an orb-weaving spider by a team filming a documentary series in Northern Ireland.

Fungi in the *Gibellula* genus are spider specialists. After a spore lands on a spider, the fungal cell sinks into the body and multiplies, consuming its host's internal organs. "If we cut through the infected spider, we don't see any spider anymore," says mycologist João Araújo of the Natural History Museum Denmark in Copenhagen. "It's just the fungal mass inside." Lollipop-shaped fruiting bodies emerge to spread spores to new hosts.

The newly discovered species is the first known *Gibellula* fungus found in cave spiders (an infected spider hangs from a cave ceiling in the photo below). Because zombified arachnids travel to cave entrances before dying, Araújo's team hypothesizes that the fungus drives spiders there because the airflow helps to disperse spores. The behavior resembles that seen in zombified ants.

Studying these fungi could aid pest control in crops and lead to medical innovations, Araújo says. For instance, the drug cyclosporine, which helps prevent rejection of transplanted organs, has origins in zombifying fungus. ✖

ARCHAEOLOGY

Ancient Amazonians mastered maize farming

By Bruce Bower

● **Water engineers in ancient South America** turned seasonally flooded Amazonian savannas into hotbeds of year-round maize farming. Casarabe people built an innovative, previously unrecognized network of drainage canals and water-storing ponds that enabled at least two maize harvests annually, scientists report in *Nature*. Large-scale maize cultivation during rainy and dry parts of the year fed the rise of Casarabe urban sprawl across Amazonian forests and savannas in Bolivia.

FROM LEFT: TIM FOGG; JOSÉ SACCONE

↑ Maize planted around a pond and along the edge of a canal, as in this illustration, may have helped Casarabe people grow the crop all year long.

Previous excavations dated Casarabe society, which covered an area of 4,500 square kilometers, to between the years 500 and 1400. Casarabe people had access to a variety of foods and crops, including maize, starchy tubers, squash, peanuts and yams. But investigators had found no evidence of Casarabe agricultural fields, raising questions about how farmers grew enough food to sustain a large population.

Using satellite images and ground surveys of Casarabe territory, geoarchaeologist Umberto Lombardo of the Autonomous University of Barcelona and colleagues identified clusters of human-made ponds in two savanna regions. Canals dug into the ground connected to many ponds. Leading away from pond clusters, canals formed drainage networks consisting of increasingly deep channels.

Soil samples from the edges of drainage canals and ponds contained microscopic mineral formations, called phytoliths, characteristic of maize. Cultivation probably occurred along canal borders and around the margins of ponds.

The findings suggest that Casarabe people turned savannas into maize-production centers rather than exploiting a range of available crops. As the population grew and environmental pressures rose, "perhaps they looked for more reliable and stable sources of proteins," Lombardo says. "Maize could have offered that to some extent." ✖

CLIMATE

Diaries disclose how people weathered the Little Ice Age

By Alex Viveros

● **"Dear diary, it was freezing outside today…"** If someone today wrote that in their journal, it might seem like an innocuous enough line. But what if, 500 years from now, scientists used that entry to answer climate mysteries?

Researchers looking to the past have done just that, combing through old diaries and other documents to reconstruct the climate of 16th century Transylvania, part of modern-day Romania. What they found offers a glimpse at how a cooling period called the Little Ice Age may have affected people in the region, the team reports in *Frontiers in Climate*.

Researchers typically rely on pollen, sediments and other natural materials to reconstruct past climate change. But "what we wanted to do is to focus on how people at the time felt the climate," says Tudor Caciora, a climatologist at the University of Oradea in Romania.

The Little Ice Age was a cooling event from the 14th to the mid-19th centuries. Average temperatures in Europe dropped by 0.5 degrees Celsius after 1560. Several studies have traced the effects of the phenomenon in Western Europe, but researchers have struggled to collect info on Eastern Europe.

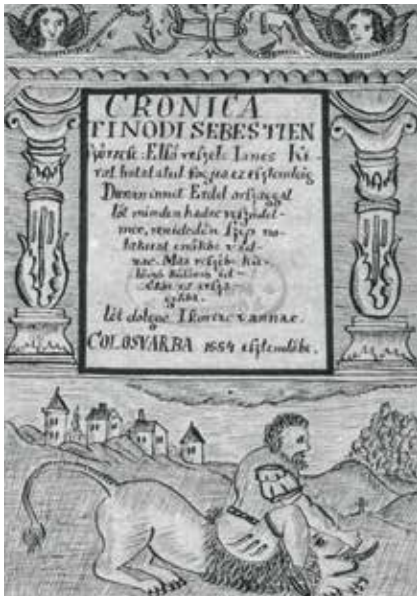
Caciora combed through documents that were handwritten by people living in Transylvania during the 1500s. The researchers had to read the documents, which were written in different languages, including Hungarian, Turkish and Latin, in their entirety. Searching for keywords like "hot weather" was not a reliable option, since people often wrote about the weather in distinct ways. A passage describing the effects of heavy rains during a siege, for example, read "a large river flowed through the city, which swelled every day and did not allow passage even for several hours."

The documents paint a picture of a region that was marked by heat and droughts in the first half of the 16th century, followed by a period of increased rainfall. Some vivid accounts indicate how the climate affected people by influencing calamities like famine, locusts and disease. One describes a drought-induced famine in the summer of 1534. People were "losing their minds because of hunger," resorting to eating herbs, tree bark and carrion. Skeletal corpses were described as having the remains of grass in their mouths.

Warm weather recorded throughout the century suggests that the Little Ice Age may have been delayed in the east compared with the west.

In addition to illuminating the past, research like Caciora's may foreshadow how extreme events could impact people in the future.

"Imagine what happens when we have a similar event in a climate that's already warmer by 2 degrees on average," says Ulrich Foelsche, a climate scientist at the University of Graz in Austria. "These studies of past climates are especially important to understand the variability of climate and extremes, to better know what could be coming up in the future." ✖



Researchers used texts like these to discern what it was like to live through the Little Ice Age in a region of Romania. ↙

O. R. GACEU *ET AL* 2024

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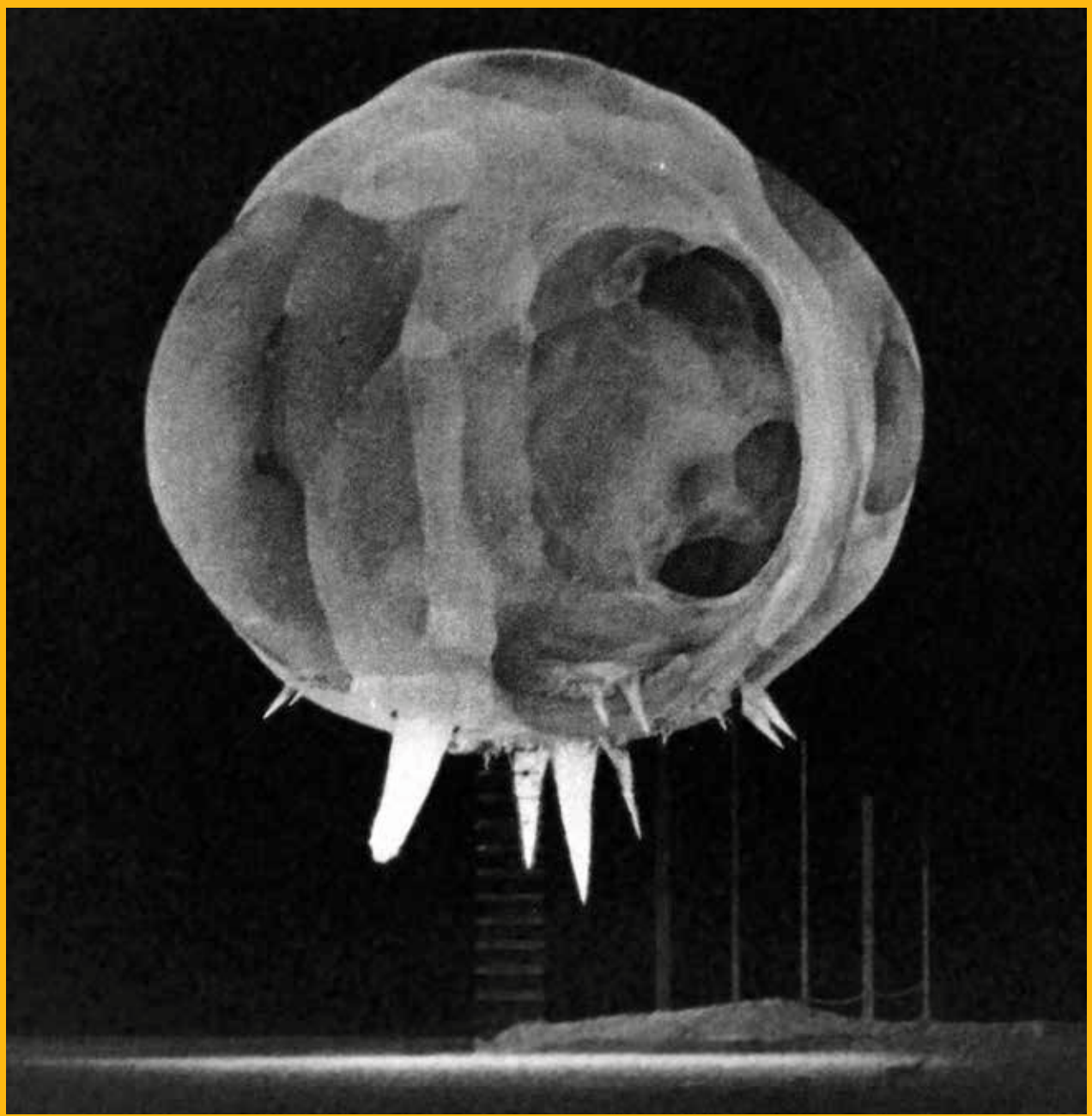


U.S. AIR FORCE

TECHNOLOGY

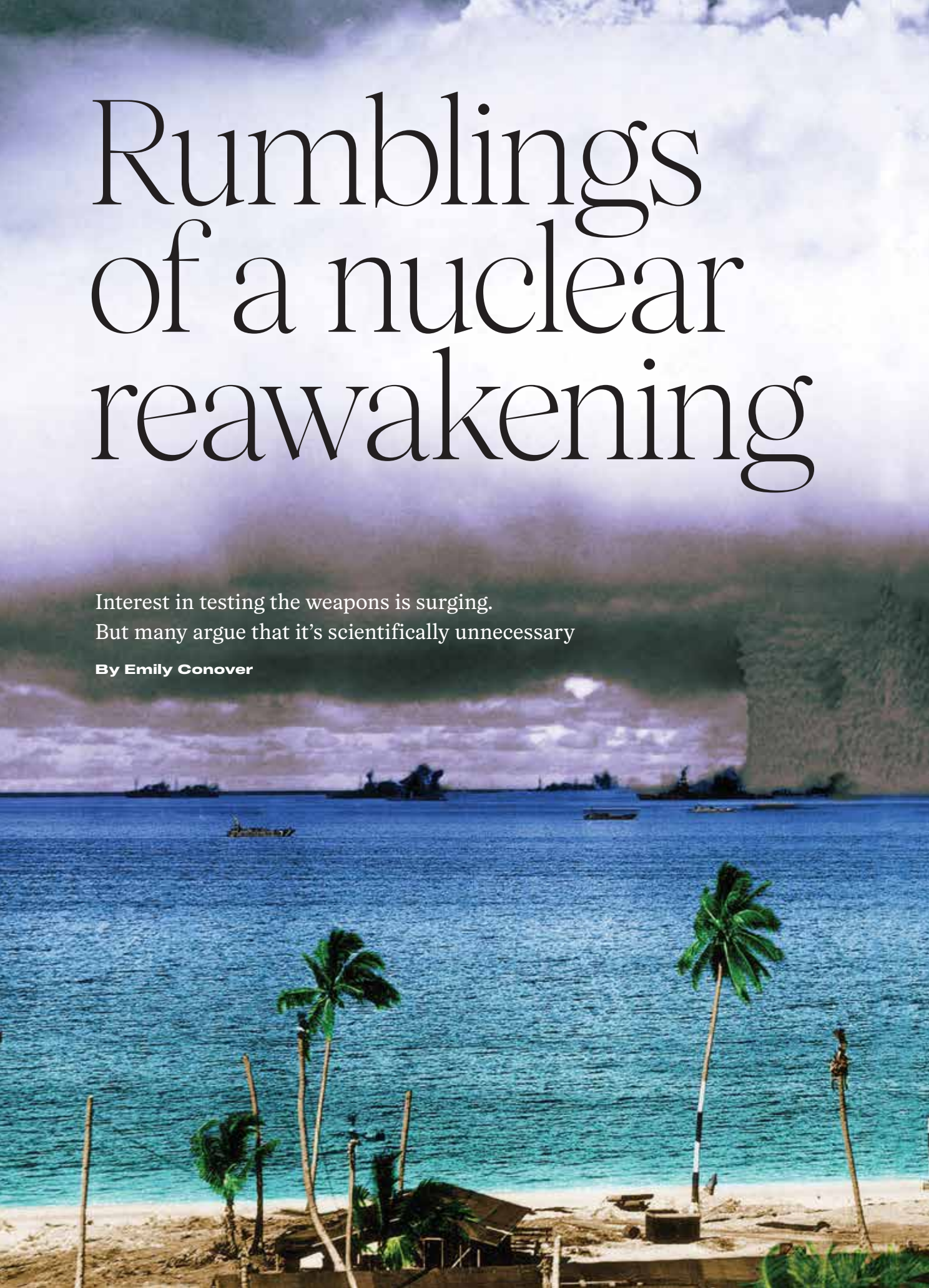
A NUCLEAR BLAST FROM THE PAST

● In 1952, during the heyday of U.S. nuclear weapons testing, the government detonated an atomic bomb in Nevada and recorded the explosion. This image of the fireball, taken a millisecond after detonation, revealed strange spikes. Dubbed rope tricks, the spikes resulted from the rapid heating and vaporization of cables tethering the bomb to the ground. The United States stopped such aboveground tests in 1962 and ceased explosive tests altogether in 1992. How nuclear weapons are studied now looks very different (see Page 32). — *Cassie Martin*

Rumblings of a nuclear reawakening

Interest in testing the weapons is surging. But many argue that it's scientifically unnecessary

By Emily Conover



In 1946, the United States conducted this nuclear test at Bikini Atoll. Tests moved underground in the 1960s to limit nuclear fallout. After decades of hiatus, the United States may resume underground tests, some experts say.

When the countdown hit zero on September 23, 1992, the desert surface puffed up into the air, as if a giant balloon had inflated it from below.

It wasn't a balloon. Scientists had exploded a nuclear device hundreds of meters below the Nevada desert, equivalent to thousands of tons of TNT. The ensuing fireball reached pressures and temperatures well beyond those in Earth's core. Within milliseconds of the detonation, shock waves rammed outward. The rock melted, vaporized and fractured, leaving behind a cavity oozing with liquid radioactive rock that puddled on the cavity's floor.

As the temperature and pressure abated, rocks collapsed into the cavity. The desert surface slumped, forming a subsidence crater about 3 meters deep and wider than the length of a football field. Unknown to the scientists working on this test, named Divider, it would be the end of the line. Soon after, the United States halted nuclear testing.

Beginning with the first explosive test, known as Trinity, in 1945, more than 2,000 atomic blasts have rattled the globe. Today, that nuclear din

has been largely silenced, thanks to the norms set by the Comprehensive Nuclear-Test-Ban Treaty, or CTBT, negotiated in the mid-1990s.

Only one nation — North Korea — has conducted a nuclear test this century. But researchers and policy makers are increasingly grappling with the possibility that the fragile quiet will soon be shattered.

Some in the United States have called for resuming testing, including a former national security adviser to President Donald Trump. Officials in the previous Trump administration considered testing, according to a 2020 *Washington Post* article. And there may be temptation in coming years. The United States is in the midst of a sweeping, decades-long overhaul of its aging nuclear arsenal. Tests could confirm that old weapons still work, check that updated weapons perform as expected or help develop new types of weapons.

Meanwhile, the two major nuclear powers, the United States and Russia, remain ready to obliterate one another at a moment's notice. If tensions escalate, a test could serve as a signal of willingness to use the weapons.

Testing "has tremendous symbolic importance," says Frank von Hippel, a physicist at Princeton University. "During the Cold War, when we were shooting these things off all the time, it was like war drums: 'We have nuclear weapons and they work. Better watch out.'" The cessation of testing, he says, was an acknowledgment that "these [weapons] are so unusable that we don't even test them."

Many scientists maintain that tests are unnecessary. "What we've been saying consistently now for decades is there's no scientific reason that we need to test," says Jill Hruby, who was the administrator of the National Nuclear Security Administration, or NNSA, during the Biden administration.

That's because the Nevada site, where nuclear explosions once thundered regularly, hasn't been mothballed entirely. There, in an underground lab, scientists are performing nuclear experiments that are subcritical, meaning they don't kick off the self-sustaining chains of reactions that define a nuclear blast. Many scientists argue that subcritical experiments, coupled with computer simulations using the most powerful supercomputers on the planet, provide all the information needed to assess and modernize the weapons. Subcritical experiments, some argue, are even superior to traditional testing for investigating some lingering scientific puzzles about the weapons, such as how they age.

Others think that subcritical experiments and simulations, no matter how sophisticated, can't replace the real thing indefinitely. But so far, the experiments and detailed assessments of the stockpile have backed up the capabilities of the nuclear arsenal. And those experiments avoid the big drawbacks of tests.

"A single United States test could trigger a global chain reaction," says geologist Sulgiye Park of the Union of Concerned Scientists, a nonprofit advocacy group. Other nuclear powers would likely follow by setting off their own test blasts. Countries without nuclear weapons might be spurred to develop and test them. One test could kick off a free-for-all. "It's like striking a match in a roomful of dynamite," Park says.

A rising threat

The logic behind nuclear weapons involves mental gymnastics. The weapons can annihilate entire cities with one strike, yet their existence is touted as a force for peace. The thinking is that nuclear weapons act as a deterrent — other countries will resist using a nuclear weapon, or making any major attack, in fear of retaliation. The idea is so embedded in U.S. military circles that a type of intercontinental ballistic missile developed during the Cold War was dubbed Peacekeeper.

Since the end of testing, the world seems to have taken a slow, calming exhale. Global nuclear weapons tallies shrunk from more than 70,000 in the mid-1980s to just over 12,000 today. That pullback was due to a series of treaties between the United States and Russia (previously the Soviet Union). Nuclear weapons largely fell from the forefront of public consciousness.

But now there's been a sharp inhale. The last remaining arms-control treaty between the United States and Russia, New START, is set to expire in 2026, giving the countries free rein on numbers of deployed weapons. Russia already suspended its participation in New START in 2023 and revoked its ratification of the Comprehensive Nuclear-Test-Ban Treaty to mirror the United States and a handful of other countries that signed but never ratified the treaty. (The holdouts prevented the treaty from officially coming into force, but nations have abided by it anyway.) Nuclear threats by Russia have been a regular occurrence during the ongoing war in Ukraine. And China, with the third-largest stockpile, is rapidly expanding its cache, highlighting

← Workers prepared the diagnostics rack to monitor the underground explosion for the last U.S. nuclear test, called Divider, in the Nevada desert in 1992.

PREVIOUS SPREAD: SCIENCE HISTORY IMAGES/ALAMY STOCK PHOTO; THIS SPREAD: COURTESY OF LOS ALAMOS NATIONAL LABORATORY

a potential future in which there are three main nuclear powers, not just two.

"There is this increasing perception that this is a uniquely dangerous moment.... We're in this regime where all the controls are coming off and things are very unstable," says Daniel Holz, a physicist at the University of Chicago and chair of the Science and Security Board of the Bulletin of the Atomic Scientists, a nonprofit that aims to raise awareness of the peril of nuclear weapons and other threats. In January, the group set its metaphorical Doomsday Clock at 89 seconds to midnight — the closest it has ever been.

Some see the ability to test as a necessity for a world in which nuclear weapons are a rising threat. "We are seeing an environment in which the autocrats are increasingly relying on nuclear weapons to threaten and coerce their adversaries," says Robert Peters, a research fellow at the Heritage Foundation, a conservative think tank. "If you're in an acute crisis or conflict in which your adversary is threatening to employ nuclear weapons, you don't want to limit the options of the president to get you out of that crisis." Testing, and the signal it sends to an adversary, he argues, should be such an option.

Peters advocates for shortening the time window for test preparations — currently estimated at two or three years — to three to six months. The Heritage Foundation's Project 2025 calls for "immediate test readiness."

The United States regularly considers the possibility of testing nuclear weapons. "It's a question that actually gets asked every year," says Thom Mason, director of Los Alamos National Laboratory in New Mexico. Los Alamos is one of the three U.S. nuclear weapons labs, alongside Lawrence Livermore National Laboratory in California and Sandia National Laboratories in Albuquerque. Each year, the directors of the three labs coordinate detailed assessments of the stockpile's status, including whether tests are needed.

"Up until this point, the answer has been 'no,'" Mason says. But if scientific concerns arose that couldn't be resolved otherwise or if weapons began unexpectedly deteriorating, that assessment could change.

KAREN KASMAUSKI/CORBIS DOCUMENTARY/GETTY IMAGES PLUS

"A single United States test could trigger a global chain reaction."

—Sulgiye Park

← Craters mark where nuclear devices were detonated underground at the Nevada National Security Sites.

If a test were deemed necessary, exactly how long it would take to prepare would depend on the reasons for it. "If you're trying to answer a scientific question, then you probably need lots of instrumentation and that could take time," Mason says. "If you're just trying to send a signal, then maybe you don't need as much of that; you're just trying to make the ground shake."

Testing without tests

The area of the Nevada desert encompassing the test site is speckled with otherworldly Joshua trees and the saucer-shaped craters of past tests. In addition to 828 underground tests, 100 atmospheric tests were performed there, part of what's now known as the Nevada National Security Sites. Carved out of Western Shoshone lands, it sits 120 kilometers from Las Vegas. Radioactive fallout from atmospheric tests, which ceased in 1962, reached nearby Indian reservations and other communities — a matter that is still the subject of litigation.

By moving tests underground, officials aimed to contain the nuclear fallout and limit its impact on human health. Before an underground test, workers outfitted a nuclear device with scientific instruments and lowered it into a hole drilled a few hundred meters into the earth. The hole was then filled with sand, gravel and other materials.

As personnel watched a video feed from the safety of a bunker, the device was detonated. "You see the ground pop, and you see the dust come up and then slowly settle back down. And then eventually you see the subsidence crater form. It just falls in on itself," says Marvin Adams, a nuclear engineer who was deputy administrator for NNSA's Defense Programs during the Biden administration. "There was always a betting pool on how long that would take before the crater formed. And it could be seconds, or it could be days."

Kilometers' worth of cables fed information from the equipment to trailers where data were recorded. Meanwhile, stations monitored seismic signals and radioactivity. Later, another hole would be drilled down into the cavity and rock samples taken to determine the explosion's yield.

Today, such scenes have gone the way of the '90s hairstyles worn in photos of underground test preparation. They've been replaced by subcritical experiments, which use chemical explosives to implode or shock plutonium, the fuel at the heart of U.S. weapons, in a facility called the Principal Underground Laboratory for

Subcritical Experimentation, PULSE.

The experiments mimic what goes on in a real weapon but with one big difference. Weapons are supercritical: The plutonium is compressed enough to sustain chains of nuclear fission reactions, the splitting of atomic nuclei. The chain reactions occur because fission spits out neutrons that, in a supercritical configuration, can initiate further fissions, which release more neutrons, and so on. A subcritical experiment doesn't smoosh the plutonium enough to beget those fissions upon fissions that lead to a nuclear explosion.

The PULSE facility consists of 2.3 kilometers of tunnels nearly 300 meters below the surface. There, a machine called Cygnus takes X-ray images of the roiling plutonium when it's blasted with chemical explosives in subcritical experiments. X-rays pass through the plutonium and are detected on the other side. Just as a dentist uses an X-ray machine to see inside your mouth, the X-rays illuminate what's happening inside the experiment.

Glimpses of such experiments are rare. A video of a 2012 subcritical experiment shows a dimly lit close-up of the confinement vessel that encloses the experiment over audio of a countdown and a piercing beeping noise, irritating enough that it must be signifying something important is about to happen. When the countdown ends, there's a bang, and the beeping stops. That's it. It's a far cry from the mushroom clouds of yesteryear.

The experiments are a component of the U.S. stockpile stewardship program, which ensures the weapons' status via a variety of assessments, experiments and computer simulations. PULSE is now being expanded to beef up its capabilities. A new machine called Scorpius is planned to begin operating in 2033. It will feature a 125-meter-long particle accelerator that will blast electrons into a target to generate X-rays that are more intense and energetic than Cygnus', which will allow scientists to take images later in the implosion. What's more, Scorpius will produce four snapshots at different times, revealing how the plutonium changes throughout the experiment. And the upcoming ZEUS, the Z-Pinched Experimental Underground System, will blast subcritical experiments with neutrons and measure the release of gamma rays, a type of high-energy radiation. ZEUS will be the first experiment of its kind to study plutonium.

Subcritical experiments help validate computer simulations of nuclear weapons. Those simulations then inform the maintenance and development of the real thing. The El Capitan computer, installed for this purpose at Lawrence Livermore in 2024, is the fastest supercomputer ever reported.

That synergy between powerful computing and advanced experiments is necessary to grapple with the full complexity of modern nuclear weapons, in which materials are subject to some of the most extreme conditions known on Earth and evolve dramatically over mere instants.

To maximize the energy released, modern weapons don't stop with fission. They employ a complex interplay between fission and fusion, the merging of atomic nuclei. First, explosives implode the plutonium, which is contained in a hollow sphere called a "pit." This allows fission reactions to proliferate. The extreme temperatures and pressures generated by fission kick off fusion reactions in hydrogen contained inside the pit, blasting out neutrons that initiate additional fission. X-rays released by that first stage compress a second stage, generating additional fission and fusion reactions that likewise feed

In the tunnels of the PULSE facility (left), physicists use the Cygnus machine (right) to analyze plutonium in subcritical experiments designed to avoid sustained nuclear chain reactions. ↘

off one another. These principles have produced weapons 1,000 times as powerful as the bomb dropped on Hiroshima.

To mesh simulations and experiments, scientists must understand their measurements in detail and carefully quantify the uncertainties involved. This kind of deep understanding wasn't as necessary, or even possible, in the days of explosive nuclear weapons test, says geophysicist Raymond Jeanloz of the University of California, Berkeley. "It's actually very hard to use nuclear explosion testing to falsify hypotheses. They're designed mostly to reassure everyone that, after you put everything together and do it, that it works."

Laboratory experiments can be done repeatedly, with parameters slightly changed. They can be designed to fail, helping delineate the border between success and failure. Nuclear explosive tests, because they were expensive, laborious one-offs, were designed to succeed.

Stockpile stewardship has allowed scientists to learn the ins and outs of the physics behind the weapons. "We pay attention to every last detail," Hruby says. "Through the science program, we now better understand nuclear weapons than we ever understood them before."

For example, Jeanloz says, in the era of testing, a quantity called the energy balance wasn't fully understood. It describes how much energy gets transferred from the primary to the secondary component in a weapon. In the past, that lack of understanding could be swept aside, because a test could confirm that the weapons worked. But with subcritical experiments and simulations, fudge factors must be eliminated to be certain a weapon will function. Quantifying that energy balance and determining the uncertainty was a victory of stockpile stewardship.

This type of work, Jeanloz says, brought "the heart and soul, the guts of the scientific process into the [nuclear] enterprise."

To test or not to test

Subcritical experiments are focused in particular on the quandary over how plutonium ages. Since 1989, the United States hasn't fabricated significant numbers of plutonium pits. That means the pits in the U.S. arsenal are decades old, raising questions about whether weapons will still work.

An aging pit, some scientists worry, might

BOTH: COURTESY OF NEVADA NATIONAL SECURITY SITES

cause the multistep process in a nuclear warhead to fizzle. For example, if the implosion in the first stage doesn't proceed properly, the second stage might not go off at all.

Plutonium ages not only from the outside in — akin to rusting iron — but also from the inside out, says Siegfried Hecker, who was director of Los Alamos from 1986 to 1997. "It's constantly bombarding itself by radioactive decay. And that destroys the metallic lattice, the crystal structure of plutonium."

The decay leaves behind a helium nucleus, which over time may result in tiny bubbles of helium throughout the lattice of plutonium atoms. Each decay also produces a uranium atom that zings through the material and "beats the daylights out of the lattice," Hecker says. "We don't quite know how much the damage is ... and how that damaged material will behave under the shock and temperature conditions of a nuclear weapon. That's the tricky part."

One way to circumvent this issue is to produce new pits. A major effort under way will ramp up production. In 2024, the NNSA "diamond stamped" the first of these pits, meaning that the pit was certified for use in a weapon. The aim is for the United States to make 80 pits per year by 2030. But questions remain about new plutonium pits as well, Hecker says, as they rely on an updated manufacturing process.

Hecker, whose tenure at Los Alamos straddled the testing and post-testing eras, thinks nuclear tests could help answer some of those questions. "Those people who say, 'There is no scientific or technical reason to test. We can do it all with computers,' I disagree strongly." But, he says, the benefits of performing a test would be outweighed by the big drawback: Other countries would likely return to testing. And those countries would have more to learn than the United States. China, for instance, has performed only 45 tests, while the United States has performed over 1,000. "We have to find other ways that we can reassure ourselves," Hecker says.

Other experts similarly thread the needle. Nuclear tests of the past produced plenty of surprises, such as yields that were higher or lower than predicted, physicist Michael Frankel, an independent scientific consultant, and colleagues argued in a 2021 report. While the researchers advise against resuming testing in the current situation, they expect that stockpile stewardship will not be sufficient indefinitely. "Too many things have gone too wrong too often to trust Lucy with the football one more time," Frankel and colleagues wrote, referring to Charles Schulz's comic strip *Peanuts*. If we rely too much on computer simulations to conclude an untested nuclear weapon will work, we might find ourselves like Charlie Brown — flat on our backs.

But other scientists have full faith in subcritical experiments and stockpile stewardship. "We have always found that there are better ways to answer these questions than to return to nuclear explosive testing," Adams says.

Defining a nuclear test

For many scientists, subcritical experiments are preferable, especially given the political ramifications of full-fledged tests. But the line between a nuclear test prohibited by the Comprehensive Nuclear-Test-Ban Treaty and an experiment that is allowed is not always clear.

The CTBT is a "zero yield" treaty; experiments can release no energy beyond that produced by the chemical explosives. But, Adams says, "there's no such thing as zero yield." Even in an idle, isolated hunk of plutonium, some nuclear fission happens spontaneously. That's a nonzero but tiny nuclear yield. "It's a ridiculous term," he says. "I hate it. I wish no one had ever said it."

The United States has taken zero yield to mean that self-sustaining chain reactions are prohibited. U.S. government reports claim that Russia has performed nuclear experiments that surpass this definition of the zero yield benchmark and raise concerns about China's adherence to the standard. The confusion has caused finger-pointing and increased tensions.

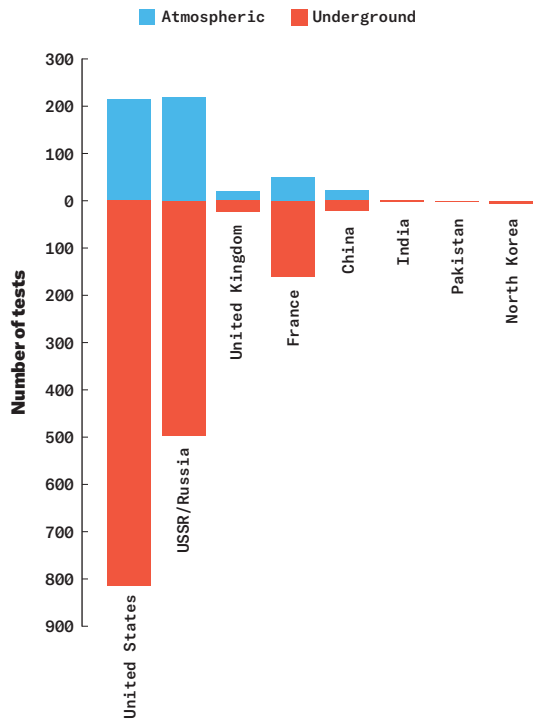
But countries might honestly disagree on the definition of a nuclear test, Adams says. For example, a country might allow "hydronuclear" experiments, which are supercritical but the amount of fission energy released is dwarfed by the energy from the chemical explosive. Such experiments would violate U.S. standards, but perhaps not those of Russia or another country.

Even if everyone could agree on a definition, monitoring would be challenging. The CTBT provides for seismic and other monitoring, but detecting very-low-yield tests would demand new inspection techniques, such as measuring the radiation emanating from a confinement vessel used in an experiment.

Testing's weight

Tests that clearly break the rules, however, can be swiftly detected. The CTBT monitoring

NUCLEAR TESTING TALLY



Since the first nuclear weapons test in 1945, there have been more than 2,000 tests. In the 1960s, countries began performing tests underground over fears of radioactive fallout. In the 1990s, nuclear testing largely ended with the arrival of the Comprehensive Nuclear-Test-Ban Treaty. The only country to test nuclear weapons in the 21st century is North Korea. Its last known test was in 2017.

system can spot underground explosions as small as 0.1 kilotons, less than a hundredth that of the bomb dropped on Hiroshima. That includes the most recent nuclear explosive test, performed by North Korea in 2017.

Despite being invisible, underground nuclear explosive tests have an impact. While an underground test is generally much safer than an open-air nuclear test, "it's not *not* risky," Park says.

The containment provided by an underground test isn't assured. In the 1970 Baneberry test in Nevada, a misunderstanding of the site's geology led to a radioactive plume escaping in a blowout that exposed workers on the site.

While U.S. scientists learned from that mistake and haven't had such a major containment failure since, the incident suggests that performing an underground test in a rushed manner could increase the risks for an accident, Park says.

Hecker is not too concerned about that possibility. "For the most part, I have good confidence that we could do underground nuclear testing without a significant insult to the environment," he says. "It's not an automatic given.... Obviously there's radioactive debris that stays down there. But I think enough work has been done to understand the geology that we don't think there will be a major environmental problem."

While the United States knows its test sites well and has practice with underground testing, "other countries might not be as knowledgeable," Hruby says. So if the United States starts testing and others follow, "the chance of a non-containment, a leak of some kind, certainly goes up." A U.S. test, she says, is "a very bad idea."

Even if the initial containment is successful, radioactive materials could travel via groundwater. Although tests are designed to avoid groundwater, scientists have detected traces of plutonium in groundwater from the Nevada site. The plutonium traveled a little more than a kilometer in 30 years. "To a lot of people, that's not very far," Park says. But "from a geology time scale, that's really fast." Although not at a level where it would cause health effects, the plutonium had been expected to stay put.

The craters left in the Nevada desert are a mark of each test's impact on structures deep below the surface. "There was a time when detonating either above ground or underground in the desert seemed like — well, that's just wasteland," Jeanloz says. "Many would view it very differently now, and say, 'No, these are very fragile ecosystems, so perturbing the water table, putting radioactive debris, has serious consequences.'"

The weight of public opinion is another hurdle. In the days of nuclear testing, protests at the site were a regular occurrence. That opposition persisted to the very end. On the day of the Divider test in 1992, four protesters made it to within about six kilometers of ground zero before being arrested.

The disarmament movement continues despite the lack of testing. At a recent meeting of nuclear experts, the Nuclear Deterrence Summit in Arlington, Va., a few protesters gathered outside in the January cold, demanding that the United States and Russia swear off nuclear weapons for good. But that option was not on the meeting's agenda. During a break between sessions, the song that played — presumably unintentionally — was "Never Gonna Give You Up." ✖

ARMS CONTROL ASSOCIATION. ADAPTED BY C. CHANG

The real biology of sex

A male-female binary doesn't encompass all of human variation

By Tina Hesman Saey

SEX IS MESSY. It's not just about chromosomes. Or reproductive cells. Or any other binary metric. Many genetic, environmental and developmental variations can produce what are thought of as masculine and feminine traits in the same person. And so biological sex, scientists say, should be viewed in all its complex glory.

"Sex is a multifaceted trait that has some components that are present at birth and some components that developed during puberty, and each of these components shows variation," says Sam Sharpe, an evolutionary biologist at Kansas State University in Manhattan.

Yet a definition of biological sex put forth by President Donald Trump designates people as

ILLUSTRATION BY REBEKKA DUNLAP

either male or female based solely on the size of the reproductive cells they make.

Millions of Americans don't fit that narrow definition — and many don't even know it.

In an executive order signed January 20, the president asserts that there are two immutable human sexes. Females are persons "belonging, at conception, to the sex that produces the large reproductive cell." Males, according to the order, make the smaller cell. On February 19, Health and Human Services Secretary Robert F. Kennedy Jr. announced that his department, which oversees most federally funded health research, will use a slight variation of these definitions in making policies. HHS defines males as people "of the sex characterized by a reproductive system with the biological function of producing sperm." Females have the reproductive system that make eggs.

"For me, the definition is really painful because it reduces a human being to their chance of reproducing," says Anna Biason-Lauber, a pediatric endocrinologist at the University of Fribourg in Switzerland.

The Trump administration's definition leaves out people who carry certain genetic variants and don't make any reproductive cells, or gametes. It makes no exceptions for them. "What does that mean for people who don't have gametes?" Sharpe asks. "It's an important question to answer because you can't have a definition of sex that doesn't apply to everyone."

Any definition of sex used to determine who can get an identification card or use a public restroom needs to account for variation, Sharpe and other researchers say.

SEX IS COMPLICATED

One thing Trump's order gets right is that there are two sizes of reproductive cells. Eggs are much larger than sperm. That's about as close to a true binary as nature gets, says Nathan Lents, a molecular evolutionary biologist at the John Jay College of Criminal Justice in New York City. "Biology doesn't operate in binaries very often."

And sex is about much more than the size of reproductive cells. Many traits ascribed to males and females fall along a spectrum with two peaks, one the average for females and the other the average for males. For instance, on average, males are taller than females and have more muscle mass, more red blood cells and a higher metabolism. But almost nobody fits in the peak for all those measures for their sex, Lents says. "There's plenty of women who are taller than plenty of men. There are plenty of women who have higher metabolic rates than some men, even though the averages are different," he says.

"If you define biological sex purely on the gametes, you're going to ignore most of what actually matters to your daily life, including in your social life," Lents adds. "Reducing sex to a binary really doesn't make a lot of sense for how we actually live."

SEX DOESN'T START AT CONCEPTION

Another problem with Trump's executive order is that no sex cells are produced at conception. Fertilized eggs "can't produce gametes,

TIMELINE TO MALE AND FEMALE

The White House defines females as "belonging, at conception, to the sex that produces the large reproductive cell" and defines males as producing the small reproductive cell. But for the first six weeks after fertilization, there are no apparent sex differences between fetuses.

1–6 weeks after fertilization
No sex differences

6–7 weeks
Development of ovaries or testes and other internal genitalia begins

8 weeks
Testosterone production begins

9 weeks
Development of external genitalia begins

14–20 weeks
Development of internal and external genitalia complete

20 weeks
Testosterone production drops

25–35 weeks
Testes fully descend into the scrotum, ovaries into the pelvis

SOURCES: P. A. AATSHA *ET AL*/*EMBRYOLOGY, SEXUAL DEVELOPMENT* 2023, AMBOSS

because they're single cells," Sharpe says.

In fact, sex development doesn't start until several weeks after conception. The exact timing is hard to pinpoint in humans, because it happens in the womb, often before people know they're pregnant, Biason-Lauber says. About six weeks into gestation, cells appear that will eventually give rise to the gonads: ovaries to make eggs or testes to produce sperm. But for a couple of weeks, she says, those cells are indistinguishable.

Scientists used to think that embryos automatically developed as female unless there were specific instructions to become male. But in the last decade, researchers found that for embryos to develop as females they need to actively dismantle male-producing structures and build ones that support female reproduction.

At about eight weeks of gestation, certain cells in what will become the testes begin to make the hormone testosterone, which is important for development of the scrotum and penis and other male reproductive organs. But male embryos don't make sperm. That's partly because testosterone production drops around week 20 of pregnancy and doesn't substantially pick back up again until puberty, allowing immature cells to morph into sperm.

Ovaries don't produce any sex hormones during development. And the uterus, fallopian tubes and the vagina develop without any input from hormones, Biason-Lauber says. Females are born with all the eggs they will ever make, but those cells are stuck in suspended animation until puberty when they can mature and be released.

SEX CHROMOSOME COMBOS VARY

Those developmental processes are partially directed by sex chromosomes. The name is somewhat of a misnomer because these two chromosomes — X and Y — have a wide range of responsibilities beyond sex determination.

The X chromosome contains hundreds of genes, including many involved in processes throughout the body such as blood clotting, color vision and brain development. The much smaller Y chromosome contains genes important for male sex development and fertility, but also ones that play a role in immunity, heart health and cancer.

Females generally have two X chromosomes, while males typically have an X and a Y. But there are plenty of variations. For instance, in Turner syndrome, women lack one X chromosome. Many do not have gametes. Instead, these women may have what are called streak gonads. "They have a piece of collagen instead of ovaries," says Biason-Lauber. They do have a uterus.

This leads Biason-Lauber to wonder, "if the definition of a woman is the presence of the big [reproductive] cells, what are these [people]?" Turner syndrome is not so rare, she says, occurring in 1 of every 2,000 to 2,500 female babies born. Some people are not diagnosed until adulthood or never diagnosed.

About 1 in every 650 male babies has two or more X chromosomes and one Y. Those men, who have Klinefelter syndrome, often don't produce sperm. Many are unaware that they carry an extra chromosome until they go for fertility treatments, Biason-Lauber says. These people have testes and penises but may not fit the Trump administration's definition of a male.

In some cases, a gene on the Y chromosome called *SRY* — important but not essential for male sex development — alters typical development. Sometimes, when chromosomes are divvied up before sperm production in an adult, *SRY* jumps out of the Y chromosome and attaches itself to an X or another chromosome. When the hitchhiking gene, but not the rest of the Y chromosome, is passed on to offspring, it may result in people who have two X chromosomes plus a stray *SRY*. Those people often develop as male.

Some people have an X and a Y

> "The definition is really painful because it reduces a human being to their chance of reproducing."
>
> ANNA BIASON-LAUBER

chromosome but carry a version of *SRY* or other genes that don't spur typical male development. They develop as female but don't make gametes.

Still other people with an X and a Y may have genetic variants that prevent their bodies from responding to testosterone and other male sex hormones called androgens. People with complete androgen insensitivity have testes inside the abdomen, but the rest of the body develops as female. These people have the small reproductive cells, which don't usually mature, but they're not men, Biason-Lauber says.

Variants in many other genes may also prevent production of either large or small reproductive cells. Some people even have different combinations of sex chromosomes in different cells in their bodies.

BEING INTERSEX ISN'T ALL THAT RARE

About 1.7 percent of the population is intersex and doesn't fit neatly into male and female boxes, according to InterAct, an advocacy organization for intersex youth. That's as common as having naturally red hair. Intersex people may have any of a wide variety of sex development differences, including Turner syndrome, androgen insensitivity, Klinefelter syndrome and others.

Some may be born with both ovarian and testicular tissue, and thus might be classified as both male and female under the terms of the executive order, says Sylvan Fraser Anthony, InterAct's legal and policy director.

Intersex people often undergo surgeries as infants or young children to make their genitals or internal organs conform to the sex their parents choose. They may also need to take hormones to maintain their health, says Sharpe, who worries that a binary definition of sex could be used to deny intersex people access to health care.

Such sex hormones also "play an important role in many facets of development, including whether your skin is painfully dry or not, or how tall you grow during puberty, or whether you're able to maintain bone density," Sharpe says.

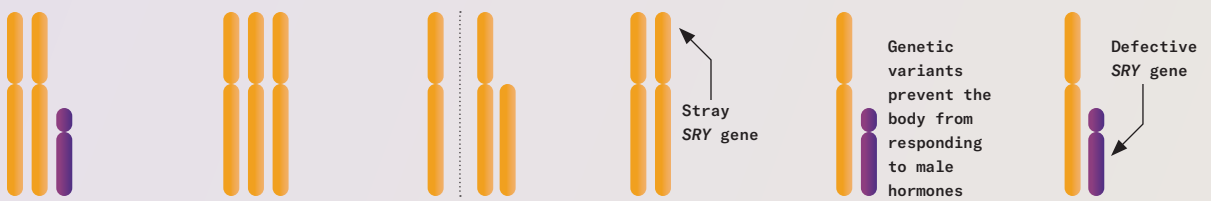
Choosing any single definer of sex is bound to sow confusion.

"If [they] use chromosomes, there's a whole lot of individuals who will be quite surprised to learn that they're male," Lents says. "If they use gametes, they're going to exclude some individuals ... but they'll also potentially open the door to including people that they didn't intend." For instance, people who have X and Y chromosomes but make female gametes would be eligible under the definition to compete in women's sports.

"The biology of sex and gender makes it very clear," Lents says. "These are not hard categories with clear definitions." ✖

MIX-AND-MATCH CHROMOSOMES

The X (yellow) and Y (purple) chromosomes are often called the sex chromosomes. Females typically have two X's, males an X and a Y. But a variety of combinations are found among humans—some quite commonly (some shown below). Typically, people with atypical sex chromosome pairings do not produce eggs or sperm. Trisomy X, in which a person has three X chromosomes, is one exception; these women usually make viable eggs.



Klinefelter syndrome
1 in 650 newborns assigned male at birth

Trisomy X
1 in 1,000 newborns assigned female at birth

Turner syndrome
1 in 2,000 newborns assigned female at birth

De la Chapelle syndrome
1 in 20,000 newborns assigned male at birth

Androgen insensitivity
2 to 5 in 100,000 newborns assigned female at birth

Swyer syndrome
1 in 80,000 newborns

DATA: MEDLINEPLUS/NATIONAL LIBRARY OF MEDICINE; GRAPHIC: B. PRICE

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ILLUSTRATION BY ALEX WILLIAMSON

The problem with carbon credits

Some projects aren't delivering true emissions offsets. Can the market be fixed? **By Alka Tripathy-Lang**

Taylor Swift may not be the first person who comes to mind when you think about climate change. But more than once, the singer has found herself in the middle of a media storm over her carbon dioxide emissions. Swift regularly hops aboard her private jet, as she did in 2024 to get from a concert in Tokyo to the Super Bowl in Las Vegas the next day. A spokesperson said that Swift purchases more than enough carbon credits to offset her jet-setting. But fans and haters alike want to know: Is it enough?

If you travel by plane, even in less-glamorous economy, you've probably faced a similar question. Airlines often offer passengers the option to pay a few extra dollars to offset their share of the flight's emissions. It's considered the climate-friendly thing to do. By purchasing carbon credits, you're paying someone somewhere to take some action — probably saving an existing forest or perhaps planting trees — that reduces total global emissions enough to cover your contribution. You can take off without a guilty conscience. Supposedly.

Over the last few years, though, carbon credits have faced increasing scrutiny. A string of academic studies and media investigations have concluded that many credits do not represent genuine emissions savings. One investigation concluded that over 90 percent of carbon credits issued for rainforest protection by the largest carbon credit certification body "had no benefit to the climate." Two reports published in 2023 found that credits for forest-based projects in North America, South America, Africa and Asia may in fact increase net emissions.

That same year, uncertainty over the validity of credits caused the voluntary carbon market to collapse; the market's value dropped by more than 60 percent. Given the current situation, "it's nearly impossible to be certain that what you're buying is high integrity," says Stephen Lezak, a researcher at the Berkeley Carbon Trading Project at the University of California, Berkeley.

Amid all the controversy, it's not clear what a consumer (celebrity or not) should do. To buy or not to buy? But understanding what carbon credits are, how they work and why the system has gone wrong can help.

What are carbon credits?

As concern over climate change has grown, governments, companies, organizations and individuals have sought ways to reduce greenhouse gas emissions to keep the global average temperature to no more than 1.5 degrees Celsius above pre-industrial levels. Many are working toward net-zero goals, meaning that at some point in the future — by 2050 at the latest — any CO_2 emitted must be counterbalanced by eliminating emissions elsewhere or taking CO_2 out of the atmosphere.

Achieving net zero should begin with every effort to eliminate or reduce the burning of fossil fuels, the

main cause of global warming, says Kaya Axelsson, head of policy and partnerships at Oxford Net Zero, a research program at the University of Oxford.

Offsetting via carbon credits is another way to balance the carbon checkbook. The idea first took hold in the 1980s and picked up in the following decade. Industrialized countries that ratified the 1997 Kyoto Protocol became part of a mandatory compliance market, in which a cap-and-trade system limited the quantity of greenhouse gases those countries could emit. An industrialized country emitting over its cap could purchase credits from another industrialized country that emitted less than its quota. Emitters could also offset CO_2 by investing in projects that reduced emissions in developing countries, which were not required to have targets. "The atmosphere doesn't care where the emissions reductions happen," says Barbara Haya, director of the Berkeley Carbon Trading Project.

The United States, which did not ratify the Kyoto Protocol, is not part of any compliance market, but such markets exist within the country. California's cap-and-trade program, for one, requires the participation of about 450 businesses responsible for about 85 percent of the state's greenhouse gas emissions.

According to the United Nations, countries' commitments are falling short of what's needed to reign in rising temperatures. And President Donald Trump withdrew the United States from the 2015 Paris Agreement, which superseded the Kyoto Protocol. The voluntary carbon market offers a private sector alternative to compliance markets.

Demand for a voluntary market took off in the early 2010s as more companies took on net-zero goals for public relations or ethical reasons, or both. One carbon credit represents one metric ton of CO_2, either removed from the atmosphere or not emitted in the first place. Since the voluntary market's inception, some 2 billion carbon credits have been issued, equivalent to about 5 percent of global annual emissions.

Offsetting is often cheaper than reducing, especially in cases where emissions-free options aren't readily available, such as with jet fuel in the airline industry. If the cost to directly abate one ton of emissions is $1,000, but a company can buy a credit for much less, offsetting may make more sense, and cents.

Credits for removing CO_2 are usually straightforward, Lezak says. Whether it's sucked from the air

ICONS: THE NOUN PROJECT, ADAPTED BY T. TIBBITTS

CARBON CREDITS 101

Buying carbon credits offers companies or individuals a way to offset their greenhouse gas emissions. One credit represents one metric ton of carbon dioxide that has been removed from the air (as through carbon capture and storage) or not emitted (as through forest preservation). Once a project begins, the developer calculates how much carbon will be removed or avoided by following the rules of a certification body. An auditor signs off on the calculation and the certification body issues credits. Once used, usually for offsetting, the credit is retired.

1. Carbon offset project begins

2. Project is verified

3. Carbon credits are issued

4. Consumers buy carbon credits

5. Carbon credits are retired

What could go wrong? Carbon credits can fail to achieve offsetting for a number of reasons.

Nonadditionality

A carbon credit must be additional—the greenhouse gases would have been emitted if the project didn't exist. If a protected forest, for example, was never in jeopardy of deforestation, the carbon credit isn't preventing any emissions.

Inaccurate baseline

If a project's emissions savings are incorrectly calculated, more credits may be issued than the project will actually offset.

Leakage

A project should not increase the demand for an emitting activity. If a cattle rancher preserves forest but trees elsewhere are instead cleared for grazing land, there is no emissions reduction.

No permanence

Unforeseen circumstances, say, a wildfire in a protected forest, could cause a project to lose the carbon it has stored or removed, reversing the benefit.

and stored underground or stashed in coastlines through mangrove restoration, "you can usually point to it [and] say, I took it out of the atmosphere," he says.

But according to the Berkeley Carbon Trading Project's Voluntary Registry Offsets Database, only about 4 percent of carbon credits in the voluntary market come from pure removals projects. The other 96 percent come from projects that claim to reduce or avoid emissions. They might limit methane released from landfills or swap solar panels in for fossil fuel–based power. The largest component of credits comes from avoided deforestation, in which forests that probably would have been felled are instead preserved.

> "It's nearly impossible to be certain that what you're buying is high integrity."
>
> **Stephen Lezak**

How are carbon credits issued?

A carbon project involving forests typically begins with a landowner who is interested in taking some offsetting action. Perhaps a farmer decides not to cut down a patch of trees for agriculture. A project developer helps the landowner turn that offsetting action into carbon credits that compensate the farmer for the lack of produce — and profit. The developer works through a carbon credit certification body that's responsible for verifying the project and issuing credits. Such organizations have methodologies for calculating how much carbon will be stored and converting that amount into carbon credits.

After the project is implemented, the developer hires a third-party auditor approved by the certification body to sign off on the project. Only after this independent look will the certification body issue credits.

From there, the developer will often partner with a broker to find buyers. Brokers work on commission or buy credits from the developer and try to sell them at a profit.

Carbon credits can be bought, sold and bundled in complicated ways before they're ever used to offset emissions, Lezak says. That's the final step in the process — retiring a credit — at which point it can no longer be bought and sold. Most often, when a credit is retired, it's used to offset emissions generated from a carbon-intensive activity, like flying. But a credit can also be retired without any actual offsetting.

By bundling credits that haven't been retired and selling them in packages, brokers hedge against the reality that many credits may be of low quality, Lezak says. "The pooling mechanism gives the appearance of some protection against those risks." Yet projects that go through the certification process may suffer from overcrediting, promising more emissions reductions than they can actually achieve.

The problem of additionality

For a carbon credit to be issued, emissions reductions must be additional, meaning those greenhouse gases would have been emitted if the project didn't exist. If a landowner never planned to cut down a forest to begin with, the purported reductions are nonadditional.

Correctly calculating additionality requires accurately determining the baseline, business-as-usual scenario, says Alexander Shenkin, a forest ecosystem ecologist at Northern Arizona University in Flagstaff. But when baselines are incorrectly calculated, they usually result in too many credits being issued. A study published in 2023 in *Science*, for example, found that incorrect baselines led to carbon credits issued in the Democratic Republic of the Congo, Tanzania and Zambia with no evidence of avoided deforestation. Forests were not at risk of being cut down, so the projects were nonadditional.

Some projects, Axelsson says, "sell four or five credits for every one ton of carbon." When a business, country or individual uses meaningless credits to counterbalance their emissions, they are not achieving neutrality.

In a now famous example of overcrediting reported in the *New Yorker*, a company hired to sell credits for a project in Zimbabwe originally calculated that the project would keep about 50 million tons of CO_2 from the atmosphere. But after implementing an approved methodology, that number jumped to some 200 million credits to be issued over the course of the project. The project was paused before all credits could be issued, but by at least one estimate, the project had 30 times as many credits as it should have based on actual emissions savings.

Excess credits undercut the price of legitimate ones, according to a paper published in 2020 in the *Proceedings of the National Academy of Sciences*. When demand was high for carbon credits, as it was before 2023, the price per credit should have been high. But with a large supply of poor-quality credits flooding the market, the price stayed relatively low.

According to S&P Global, the price of nature-based avoidance

credits went from $11.50 per ton of CO_2 to just $3.50 over the course of 2023. In contrast, technological carbon capture credits hovered around $120 per ton of CO_2.

Third-party auditors can't do much to improve projects, says former auditor Thales West, a forest scientist at Vrije Universiteit Amsterdam and lead author of the papers in *Science* and *PNAS*. "All I'm doing is checking the boxes that are related to the rules.... I wouldn't have the power to say: You're not going to get the certification."

More credits mean more money for the developer. Plus, the certification body gets paid per credit issued, so there's an incentive to issue more credits. And because the developer pays the auditor, "there is a financial incentive for the auditor to sign off," says Elias Ayrey, cofounder of Renoster, a start-up that independently scores the quality of carbon projects.

If an auditor approves a project, they're more likely to get hired again, says Libby Blanchard, a political ecologist at the University of Utah in Salt Lake City. "If there's some way to make the auditing process more independent and less tied to the outcome that the auditor provides, we would have a much better and transparent market."

Even more problems

Another dilemma is that carbon credits often ignore the interconnectedness of the world; actions in one place affect what happens elsewhere. If a rancher chooses not to turn forest into lucrative cattle-grazing land, that action is additional and seems to be deserving of carbon credits. But if the demand for the beef remains, deforestation might just happen elsewhere.

"Leakage happens when supply is restricted, but demand is unchanged," Lezak says. An article in *Climate Policy* in 2021 illustrates the point. Deforestation shifted from Brazil's Amazon to the less-regulated Cerrado — an incredibly biodiverse tropical savanna — after Brazil adopted the Amazon Soy Moratorium. Under the moratorium, established in 2006, soybean traders agreed not to purchase soy grown from newly deforested Amazon lands. However, the moratorium led to a 31 percent increase in soy production in the Cerrado. Deforestation there rose by an estimated 13 percent.

Carbon projects, Lezak says, should be additional while also decreasing demand. Providing someone who cooks over an open fire with a fuel-efficient cookstove, for example, reduces emissions thanks to the increased energy efficiency. It also reduces local demand for wood, meaning less deforestation, without shifting demand elsewhere.

But even those projects may result in overcrediting, depending on how the emissions savings are calculated and how long and often the cookstoves are used. Because a project in Mozambique used stoves that couldn't withstand rain, for instance, the stoves were largely abandoned earlier than expected.

Issues of permanence — project longevity — can also plague forest projects. Though they are designed to store carbon for a century, the projects are prone to wildfires, disease and illegal logging. "If that forest doesn't last for 100 years," Blanchard says, "that carbon was only temporarily sequestered."

Developers are supposed to check on the forests every five years or so. "But if something has gone terribly wrong," Ayrey says, "the developer isn't going ... to report that." The result: "zombie" credits from failed projects that are used for offsetting.

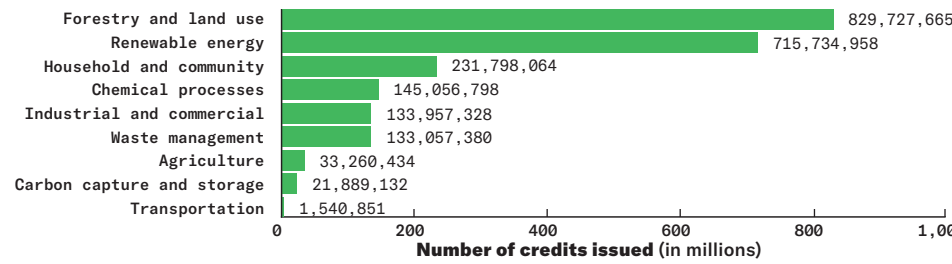
The major certification bodies require some portion of credits issued for each carbon project be set aside and held in a buffer pool to function as a kind of insurance in case of catastrophe. But buffer pools may be too small, as demonstrated in a 2022 study in *Frontiers in Forests and Global Change*. Looking at California's forest carbon offsets, researchers found that wildfires had depleted nearly one-fifth of the buffer pool in less than a decade. When also accounting for disease, the scientists concluded that the buffer pool isn't likely to guarantee the integrity of California's offsets program for the requisite century. Plus, because greenhouses gases can last in the atmosphere for thousands of years, some experts argue that the century standard is not long enough anyway.

Improving the market

Government regulation of the voluntary carbon market could help ensure that carbon credits meet a

TYPES OF CREDITS

As of the end of 2024, 2.2 billion carbon credits have been issued on the voluntary market. Nearly 70 percent come from forest management and renewable energy projects. Direct emissions removal through carbon capture and storage accounts for just 1 percent.



standard quality, Ayrey says.

Regulation could also help with transparency. Each certification body has its own registry. "You know what credits have been issued, and then the next thing you know is who's retired them, but you don't know how many times the credits were bought and sold, and by whom," Haya says. Along the way, she says, "you don't know anything about prices."

In September, the U.S. Commodity Futures Trading Commission adopted its first guidelines for the voluntary carbon market. Though guidelines do not have the same leverage as regulations, the guidelines were instrumental in bringing fraud charges against the U.S.-based developers of the Mozambique cookstove project. However, it is unclear how much of a role the government will play in more rigorously regulating the market.

For forest projects, remote-sensing technologies, which can quickly image forests in and around projects to better determine baselines, could improve transparency. Because monitoring can be monthly, weekly or even daily, satellites can also keep an eye out for leakage and permanence problems.

Independent companies that rate carbon credits are springing up to do this kind of eyes-in-the-sky work. Buyers looking to purchase high-quality credits can pay start-ups like Renoster to assess projects.

Some companies have stopped bothering with offsetting and started focusing on reducing the emissions they can control. These companies don't want to buy low-quality credits, Lezak says. They also don't want the PR backlash — or even lawsuits — that can come with false claims of neutrality, Shenkin notes.

Blanchard and colleagues argued last year in *One Earth* that credits based on emissions offsets is not a good system. Participants need to recognize that, in the market's current state, "we're not truly reducing our emissions," Blanchard says.

> "The atmosphere doesn't care where the emissions reductions happen."
>
> **Barbara Haya**

The researchers envision a framework in which offset projects are reframed as climate mitigation projects. Companies or individuals may buy carbon credits or otherwise donate to projects. But "instead of claiming that you're offsetting your emissions, you're claiming that you're contributing to global climate mitigation," Blanchard says.

This scheme would eliminate the need for brokers and other middlemen. And it would preserve many of the co-benefits that stem from some of these projects. Many forest projects, for example, double as conservation efforts that maintain air quality and biodiversity. Some projects, Ayrey says, also return some revenue to people who live in or near the forests.

Because funding is coming mostly from industrialized countries, the carbon market can bring in conservation funds to developing countries. Without the market, "there's one fewer way that we have to conserve these forests," Shenkin says.

Ultimately, though, the market must shift toward removal-based technologies, Axelsson says, and encourage investment in new technologies for carbon capture and long-term storage.

So what about airline credits?

When it comes to buying carbon credits through an airline, Axelsson says she sometimes clicks "yes" as a signal that people do care about climate change — and demand action. "But I click 'yes' knowing that that's not an offset," she says.

Another option is to estimate your emissions and support carbon projects on your own. An internet search will often reveal scandals, Ayrey says, and thus projects to avoid. Renoster also makes its reports public.

You can also vet companies based on whether they're moving toward mitigation strategies that reduce their carbon footprint. The Science Based Targets initiative dashboard captures what companies around the world have pledged to do.

In the end, if individuals want to reduce their carbon footprints, changing behavior will have a bigger impact than buying carbon credits, West argues. "You have to fly less, consume less meat, use bikes more."

Blanchard agrees. Permanently reducing your emissions, she says, "is way more meaningful." ✖

Alka Tripathy-Lang is a freelance science writer based in Arizona.

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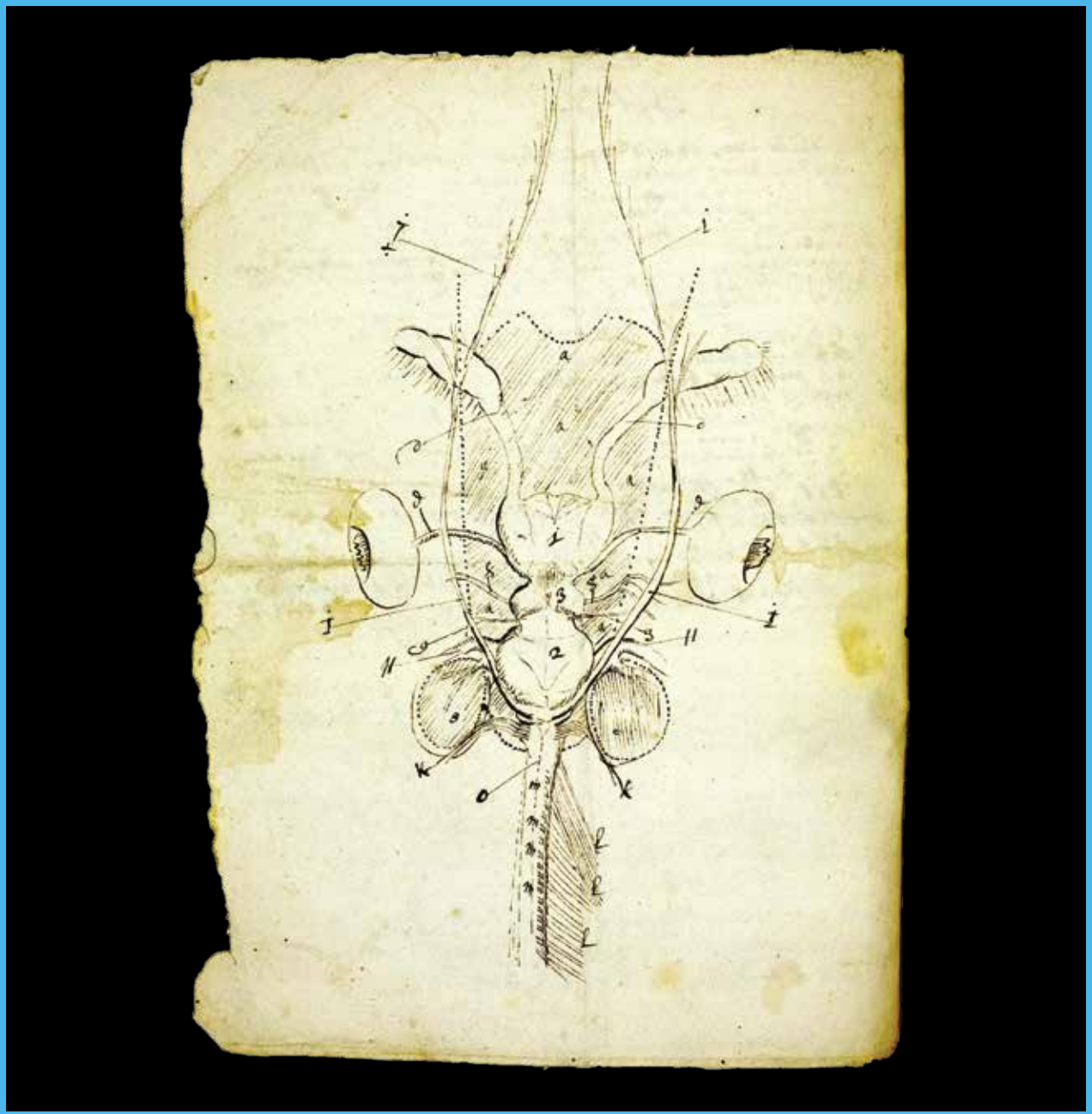

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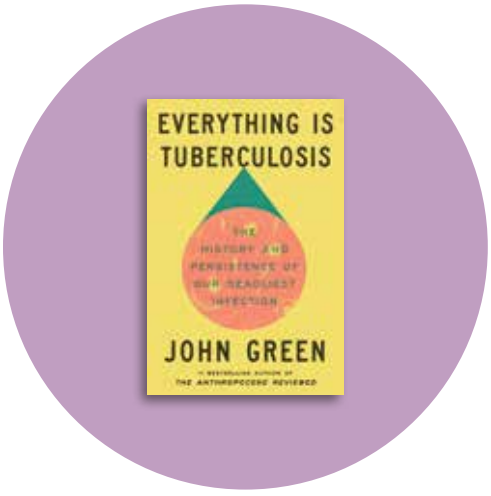
NEUROSCIENCE

BEE-HOLD THE FIRST PIC OF AN INSECT'S BRAIN

● After nearly 350 years, a sketch of a bee's brain is getting some buzz. Created in the 1670s by Dutch biologist Johannes Swammerdam and recently reported in *Notes and Records*, it is the oldest known depiction of an insect's brain. Swammerdam used a crude microscope and his knowledge of mammalian anatomy to make the drawing, which explains why it includes a cerebellum and pineal gland (2 and 3 in the sketch). Bees have neither part but have brain structures that the 17th century scientist mistook for them. — *Tina Hesman Saey*



A DISEASE WE CAN ERADICATE, BUT ONE WE CHOOSE NOT TO

By Andrea Tamayo

EVERYTHING IS TUBERCULOSIS | *John Green*
Crash Course Books | $28

A few years ago, renowned author John Green met a boy named Henry at Lakka Government Hospital in Sierra Leone. Henry was small and, at first glance, looked about 9 years old to Green. Everyone at the hospital seemed to know and love him, making Green believe he was the child of a health care worker. That is until staff revealed that Henry was a patient with multidrug-resistant tuberculosis — and that he was 17.

Henry was small because he grew up malnourished. At age 5, he became ill with tuberculosis, which waxed and waned within his body for most of his youth, further emaciating him.

Green's latest nonfiction book, *Everything is Tuberculosis*, weaves Henry's story into the social and medical history of tuberculosis — one of the world's deadliest bacterial diseases. Over 1 million people died of tuberculosis in 2023, despite our ability to cure infections with antibiotics and prevent them with vaccines. "We know how to live in a world without tuberculosis," Green writes. "But we choose not to live in that world."

That's partly due to stigma, a central theme of the book. Negative, unfair beliefs about tuberculosis have been used to dehumanize and blame people for their illness. In some communities, the sick have been shunned, thought to be cursed or possessed by demons. In 18th and 19th century Europe, the disease was romanticized as an affliction of poets and artists. Like stigma, Green argues, this belief allowed society to other the sick as fundamentally different and even accept their deaths as "divine compensation" for their poetry and art.

Today, people living with tuberculosis have told Green that fighting stigma is even harder than fighting the disease itself. Through stories of Henry and others like him, Green argues convincingly that 21st century tuberculosis is caused not by bacteria but by injustice. He retraces the path of this injustice, from the disease's racialization in the 19th and 20th centuries to the ongoing global misallocation of treatments. Green contends, for instance, that Henry might have accessed safer and more appropriate medication sooner if it weren't for where he lives. Sierra Leone's Ministry of Health couldn't afford the high costs set by U.S. pharmaceutical company Johnson & Johnson for a treatment that might have cured Henry earlier.

In the end, Green reminds readers that we all must care. "In a world where everyone can eat, and access healthcare, and be treated humanely, tuberculosis has no chance. Ultimately, we are the cause," Green writes. "We must also be the cure." ✖

"In a world where everyone can eat, and access healthcare, and be treated humanely, tuberculosis has no chance."

— John Green

HUMAN MEMORY IS IMPERFECT, AND THAT'S OK

By Laura Sanders

MEMORY LANE | *Ciara Greene and Gillian Murphy*
Princeton Univ. | $29.95

There are countless metaphors for memory. It's a leaky bucket, a steel trap, a file cabinet, words written in sand.

But one of the most evocative — and neuroscientifically descriptive — invokes Lego bricks. A memory is like a Lego tower. It's built from the ground up, then broken down, put away in bins and rebuilt in a slightly different form each time it's taken out. This metaphor is beautifully articulated by psychologists Ciara Greene and Gillian Murphy in their new book, *Memory Lane*.

Imagine your own memory lane as a series of buildings, modified in ways both small and big each time you call them to mind. "As we walk down Memory Lane, the buildings we pass — our memories of individual events — are under constant reconstruction," Greene and Murphy write.

In accessible prose, the book covers a lot of ground, from how we form memories to how delicate those memories really are. Readers may find it interesting (or perhaps upsetting) to learn how bad we all are at remembering why we did something, from trivial choices, like buying an album, to consequential ones, such as a yes or no vote on an abortion referendum. People change their reasoning — or at least, their memories of their reasoning — on these sorts of events all the time.

Modern dilemmas also come up, such as whether fake news and deepfake videos have particular sway over our memories or even create false ones. Don't panic, the authors write. Digital fakes can influence memories, sure. But so can written stories, gossip from a neighbor or a leading question from a cop. "We don't need to generate technophobic fears of a digital future where our memories will be distorted — our memories can already be distorted very effectively by nondigital means." The sentiment is alarming, but also strangely comforting.

Greene and Murphy offer another comforting message again and again: Our memories are fallible and flawed, but these slips are features, not bugs. These imperfections are a product of a flexible memory system that allows us to learn from the past, plan for the future and respond to unexpected events. Forgetting may make our brains more efficient by jettisoning extraneous fluff so we can focus on the important memories. It may even keep us happier by allowing time to ease the sting of painful experiences, the authors write. "Instead of attempting to force your memory to be something it is not, we advocate accepting it just the way it is — flaws and all." ✖

Why I Volunteer at Regeneron ISEF

CHRIS RODEE
Retired primary examiner at the U.S. Patent and Trademark Office, member of Regeneron ISEF's Judging Advisory Committee, and Category Co-Chair for ISEF

Society for Science, publisher of Science News, founded and produces the Regeneron International Science and Engineering Fair (ISEF), the largest STEM competition for high school students in the world. The competition, which launched in 1950, brings together about 2,000 students from more than 70 countries, regions and territories to compete for over $8 million in scholarships and awards. Students compete in the Society for Science's global affiliated fair network to earn an opportunity to compete at ISEF. Each year, volunteers take on roles from judging to interpreting to registering attendees. Here's what Chris RoDee, a longtime volunteer, has to say:

One of the best things about volunteering at Regeneron ISEF is the opportunity to support outstanding young people as they find their place in the world and in STEM. And that's important, because these kids can do anything they set their minds to. It's great to show them there is a place for them in science, engineering and math.

I STARTED JUDGING local and regional science fairs in the mid-2000s. I first attended ISEF in 2007 in Albuquerque, where I was a Special Awards judge. I went on to be a Grand Awards judge in Atlanta in 2008 and in Reno in 2009. I have been involved in ISEF ever since. Now I'm getting ready for Columbus this May and Phoenix in 2026.

As you meet with students, you have organic conversations and back-and-forth banter. That's when you really start to see their work, what they're excited about and what they feel is their greatest contribution. Some of the best moments are when you ask a student a question, and they give you an answer that you didn't expect, which leads to more questions and ideas. Those are the times you open up to new possibilities.

More than anything, when students come to Regeneron ISEF, they find nearly 2,000 other kids they can instantly connect with. They nerd out on all things science and engineering and are excited to learn about each other's work. It's an incredible community. As a volunteer, you help support that.

As a Regeneron ISEF volunteer, you will meet a lot of really fantastic people. If you continue volunteering, every year becomes like a reunion – you pick up exactly where you left off. You work together, trust each other. There is a real camaraderie among all the volunteers. We all have the common goal of helping these students succeed.

SOCIETY FOR SCIENCE

VOLUNTEER AT REGENERON ISEF IN COLUMBUS, OHIO, THIS MAY!
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Society for Science is a nonprofit organization best known for our award-winning journalism, world-class STEM competitions and suite of Outreach & Equity programming activities. For more than a century, our mission has been to promote the understanding and appreciation of science and the vital role it plays in human advancement: to inform, educate, and inspire.

VOL. 207 NO. 04 APRIL 2025

On display

● *Museum experts are exploring how to bring the science dioramas of yore into the 21st century, while ensuring scientific accuracy and acknowledging past biases, freelance writer Amber Dance reported in "The diorama dilemma."*

Reader Gary Hoyle reminisced about his time working as an exhibits artist and curator of natural history at the Maine State Museum. Hoyle recounted working with esteemed diorama painter Fred Scherer and learning about another renowned diorama artist, James Perry Wilson.

"Wilson was a trained architect draftsman who had worked to develop a grid pattern that minimized the distortion of viewing a curved background against the three-dimensional foreground of dioramas. His and Fred's sensitivity to light and the colors of nature astound me still," Hoyle wrote. "When painting backgrounds, they consciously modified colors to reduce the green tint from the plate glass in the viewing window."

Hoyle noted that the many scientific and artistic challenges that went into developing wildlife dioramas are now being ignored or lost to history. "What is needed is a museum devoted solely to ... these complicated, mesmerizing exhibits."

February 2025

The many scientific and artistic challenges that went into developing wildlife dioramas are now being ignored or lost to history.

Tsunami risk?

● *A Pacific submarine volcano called Axial Seamount is likely to erupt in 2025, freelance writer Rachel Berkowitz reported in "An undersea volcano may soon erupt near Oregon."*

Reader Ginger Johnson asked if the eruption could cause a tsunami.

Axial's eruptions are benign to us humans, says geophysicist William Chadwick of Oregon State University's Hatfield Marine Science Center. "The volcano is too deep, [about 1,500 meters underwater], and the kind of activity anticipated is too mild" to trigger a tsunami, he says.

What's more, tsunamis are typically caused by sudden, large movements of the seafloor, especially around subduction zones, where one tectonic plate slides beneath another. "An eruption at Axial Seamount would have no effect on the Cascadia subduction zone along the coast of Oregon, Washington and British Columbia" because the volcano is too far away, Chadwick says.

It's not nothing

● *The math puzzle "Imagine there's no zero" challenges readers to use mathematician James Foster's number system, which uses T to avoid a zero symbol.*

Reader Bill Torcaso found the number system valid but bizarre. "What about arithmetic operations?" he wrote. "'Nothing' is still important."

In general, arithmetic operations can be accommodated without a zero symbol, says puzzle maker Ben Orlin. "Negatives, for example, still work fine. Decimals are trickier but can be handled with an adapted version of scientific notation, using negative powers of T." For instance, the decimal 0.03, which is 3×10^{-2} in scientific notation, would become $3 \times T^{-2}$.

But 'nothing' is still important. "Foster has eliminated zero as a placeholder, but not as a number concept," Orlin says. "We can eradicate the zeros from every number in existence, with one very notable exception: zero itself."

Correction

✖ Due to an editing error, February's math puzzle incorrectly equated 2T with two boxed-up tens. Indeed, 2T equals 30.

SPACECRAFT NEED A BOOST TO TRAVEL BETWEEN STARS

BY AARON TREMPER

Pilots in *Star Wars* enter a dimension, hyperspace, to travel between distant worlds. To merge onto this cosmic highway, ships are equipped with special engines called hyperdrives. With the push of a lever, the spacecraft zooms faster than the speed of light, traversing between star systems in just hours or days. Han Solo and his sidekick Chewbacca make the jump to hyperspace look easy (at least when the *Millennium Falcon* is in working order).

But *Star Wars* breaks the laws of physics to achieve such a feat. Off-screen, the technology to reach another star system doesn't yet exist. However, emerging propulsion methods could brighten the future of interstellar travel.

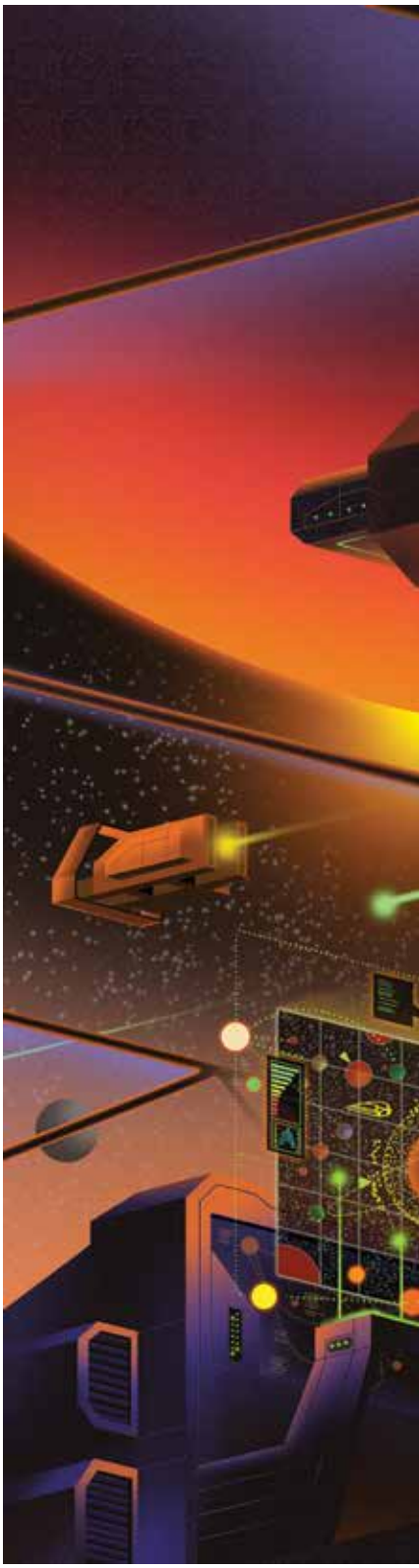
Due to the nature of light and energy, it's impossible to reach the speed of light, nearly 300,000 kilometers per second. It would take an infinite amount of energy. The fastest any human-made object has traveled is only about 0.06 percent of that speed. At that rate, it would take about 6,600 years to reach the nearest exoplanet, Proxima Centauri b, 4.24 light-years away.

A spacecraft traveling at one-tenth of the speed of light could shave the trip down to a quick 40 years. Future engineers could use nuclear power to achieve that, says Scott Bailey, an engineer at Virginia Tech. But developing that technology could take thousands of years.

Controlled fusion could help, says Cole Miller, an astronomer at the University of Maryland in College Park. Controlled fusion harnesses energy from combining atomic nuclei to create a steady supply of power. Researchers have been working on controlled fusion for about 70 years. But so far, these experiments have yet to produce more energy than they consume.

Not all vehicles in the *Star Wars* universe rely on hyperdrives; some "sun jammers" have huge sails that catch stellar winds — the constant stream of charged particles produced by stars — to move through space like a ship on the sea.

Recently, the nonprofit Planetary Society tested a similar concept. The crowdfunded LightSail 2 launched in 2019 and orbited Earth for about three years. Rather than relying on solar wind, though, the small craft's solar sails used pressure from sunlight itself. Although



GLENN HARVEY

light doesn't have mass, it does have momentum. The solar sails intercepted sunlight with thin sheets made of reflective Mylar and other polymers. When speeding photons hit the sail, they bounced.

Using solar sails to propel a large spacecraft would be tough, Miller says. The thrust produced probably wouldn't be strong enough to carry ships ferrying humans. Upscaling solar sails would offer unique benefits, however. Using sunlight would allow a spaceship to accelerate without fuel. And unlike objects on Earth, spacecraft aren't slowed by air friction produced by an atmosphere. This would allow any spacecraft to continue gaining speed as long as it's exposed to sunlight.

For now, spacefarers aren't looking to travel to another star system. But even travel within the solar system, say, to Mars, could use a boost. To safely bring people to and from the Red Planet, some researchers are looking to ion engines. These thrusters create force by shooting charged atoms from the back of a spacecraft. *Star Wars*' TIE Fighters, like the one flown by Darth Vader, navigate through space battles with them. But real ion engines work best with straight paths, says Jarred Young, an engineer at the University of Maryland. "It's essentially point-and-click propulsion."

Ion engines aren't as powerful as the chemical propellants in rockets, which create thrust by combusting fuel and oxygen-releasing substances called oxidizers. But chemical rockets burn for only a short time. Ion engines can last months or even years, possibly helping fuel trips to Mars, if engineers can design strong enough thrusters.

For now, reaching distant new worlds is only possible in fictional galaxies far, far away. ✖

THE LESSER FOOL

BY BEN ORLIN

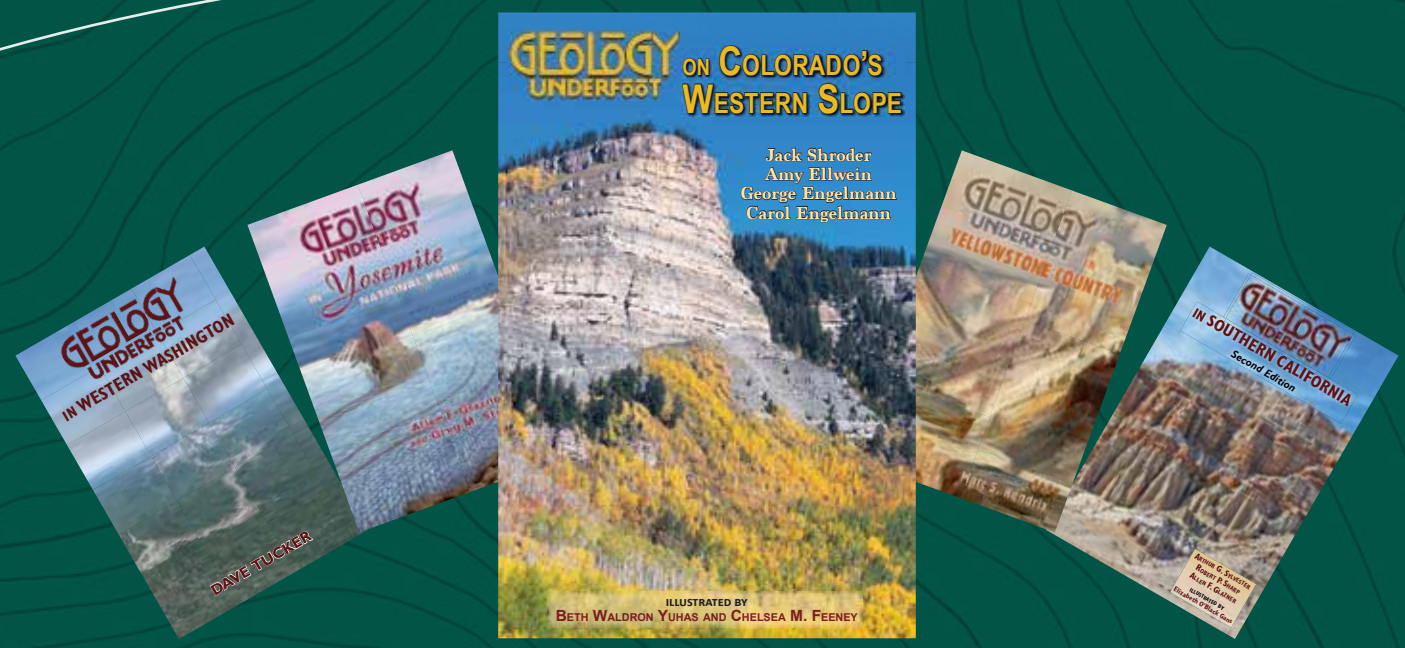
In honor of April Fools' Day, I offer the puzzling case of the Lesser Fool. In a fictional town, there lived an odd wanderer. People would present him with two amounts of money or goods and ask which is greater. Even though they offered to give him whichever amount he chose, the Fool would always select the smaller one. People came from afar just to test him. Whatever the currency, whatever the quantities, whatever convoluted form the question took, he picked the amount worth less — and then strolled away cheerfully. The following are some of the questions the Lesser Fool was asked. Can you get them right?

1. "Which is greater," asked a business tycoon, "twelve thousand and twelve dollars, or eleven thousand eleven hundred and eleven dollars?"
2. "Which is greater," asked a grandmother, holding up a pie sliced finely enough to feed all of her grandchildren, "19/200 of this pie, or 29/300 of it?"
3. "Which is worth more," asked a bank teller, "1 kilogram of quarters, or 25 kilograms of pennies?"
4. "Which is greater," asked a clockmaker, "a penny for every second in a month, or a penny for every hour in a century?" (The Fool answered with mental math alone.)
5. "Which is greater," asked an engineer, "the tenth root of $10, or the cube root of $2?" (The Fool used pencil and paper for this one.)
6. "Consider these two envelopes," said a lawyer. "The first contains $10 plus half of what's in the second. The second contains $20 minus half of what's in the first. Which envelope has more money?"
7. "I've got an exciting but volatile fund," said a hedge fund manager. "In our first year, we gained 90 percent. In our second year, we lost 50 percent. Would you rather have the amount we originally invested, or our current value?"

Bonus: One day, a child approached the Fool. "To answer so reliably, you must know which amount is larger. So why do you always take the smaller?" the child asked. "And if you're called the Lesser Fool, who's the Greater Fool?" The Fool only smiled. Can you answer the child's questions? ✖

Visit **sciencenews.org/puzzle-answers** for answers. We will publish science-themed crossword puzzles and math puzzles on alternating months. We'd love to hear your thoughts at **puzzles@sciencenews.org**.

GEOLOGY UNDERFOOT



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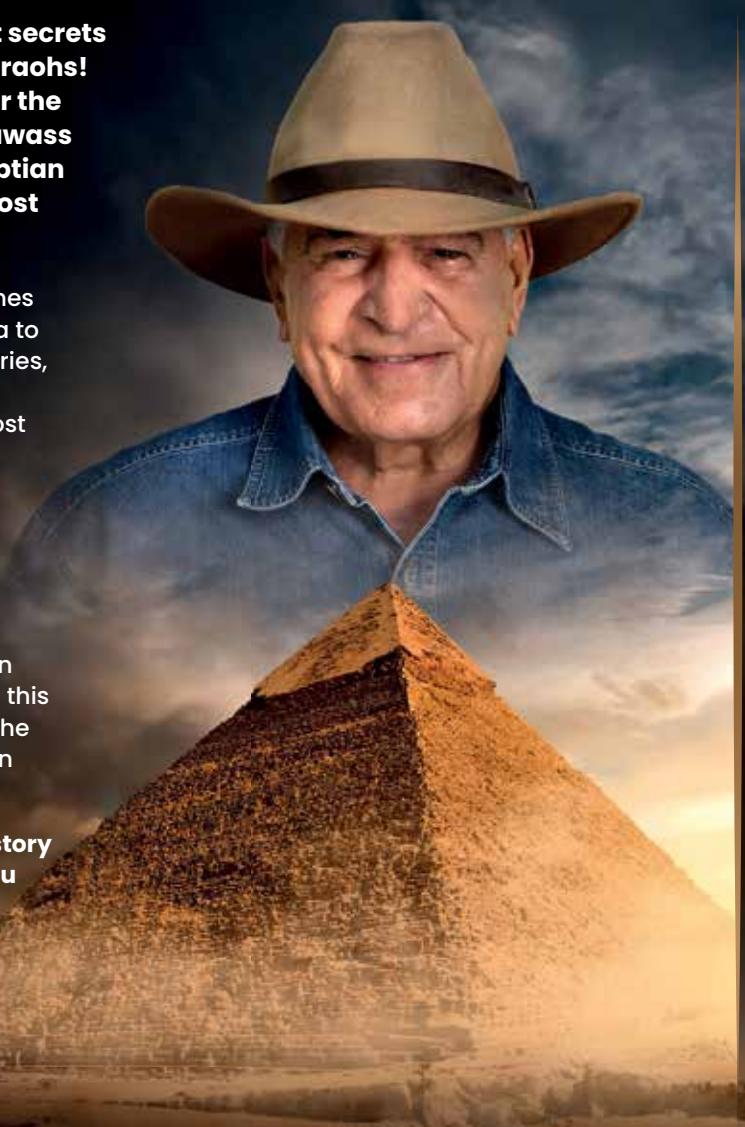

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