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Plutonium Pits

Misdiagnosing Dyslexia

The Enduring Mystery of Dark Energy

SPECIAL REPORT

The New Nuclear Age

Inside America's plan to remake its atomic arsenal

DECEMBER 2023
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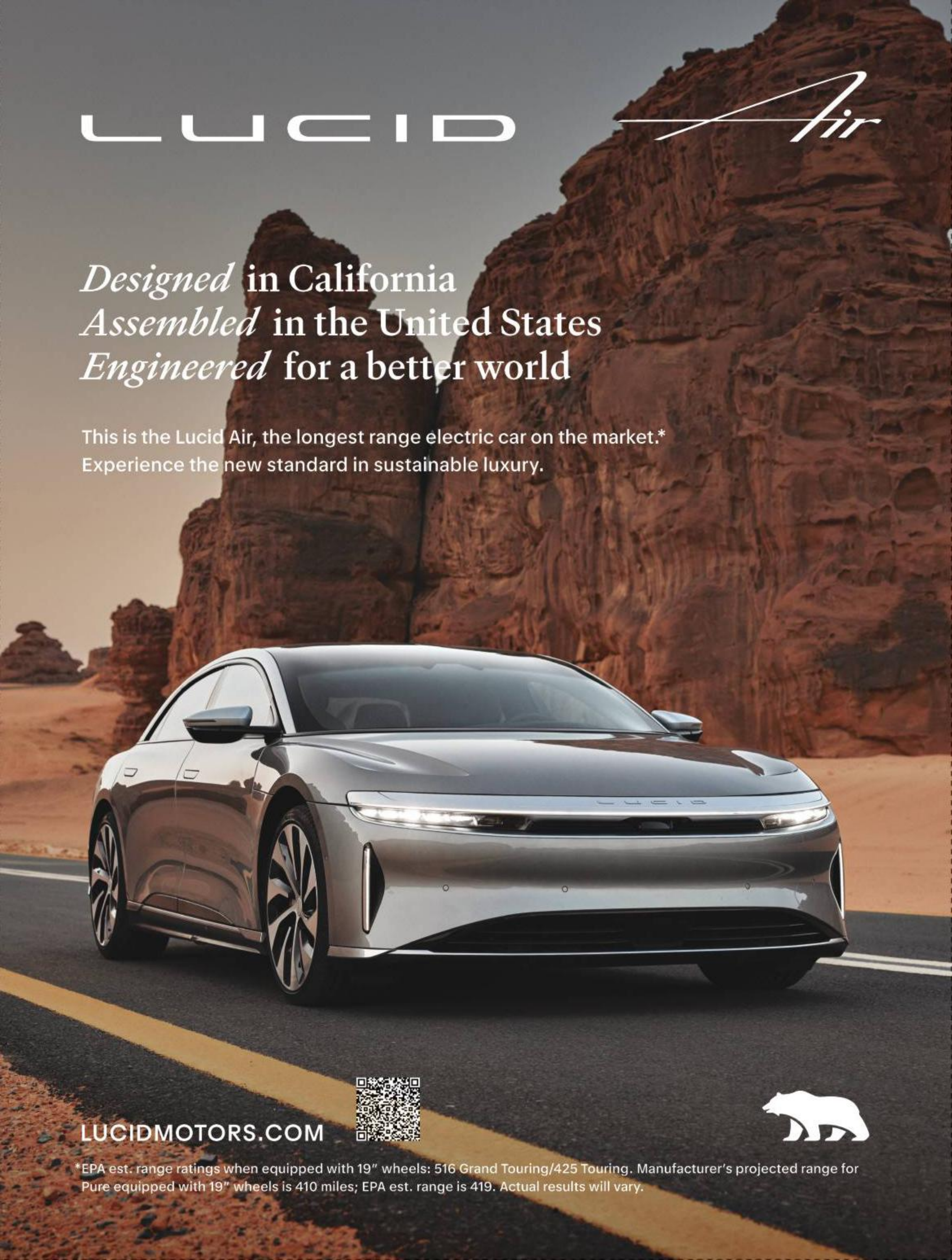
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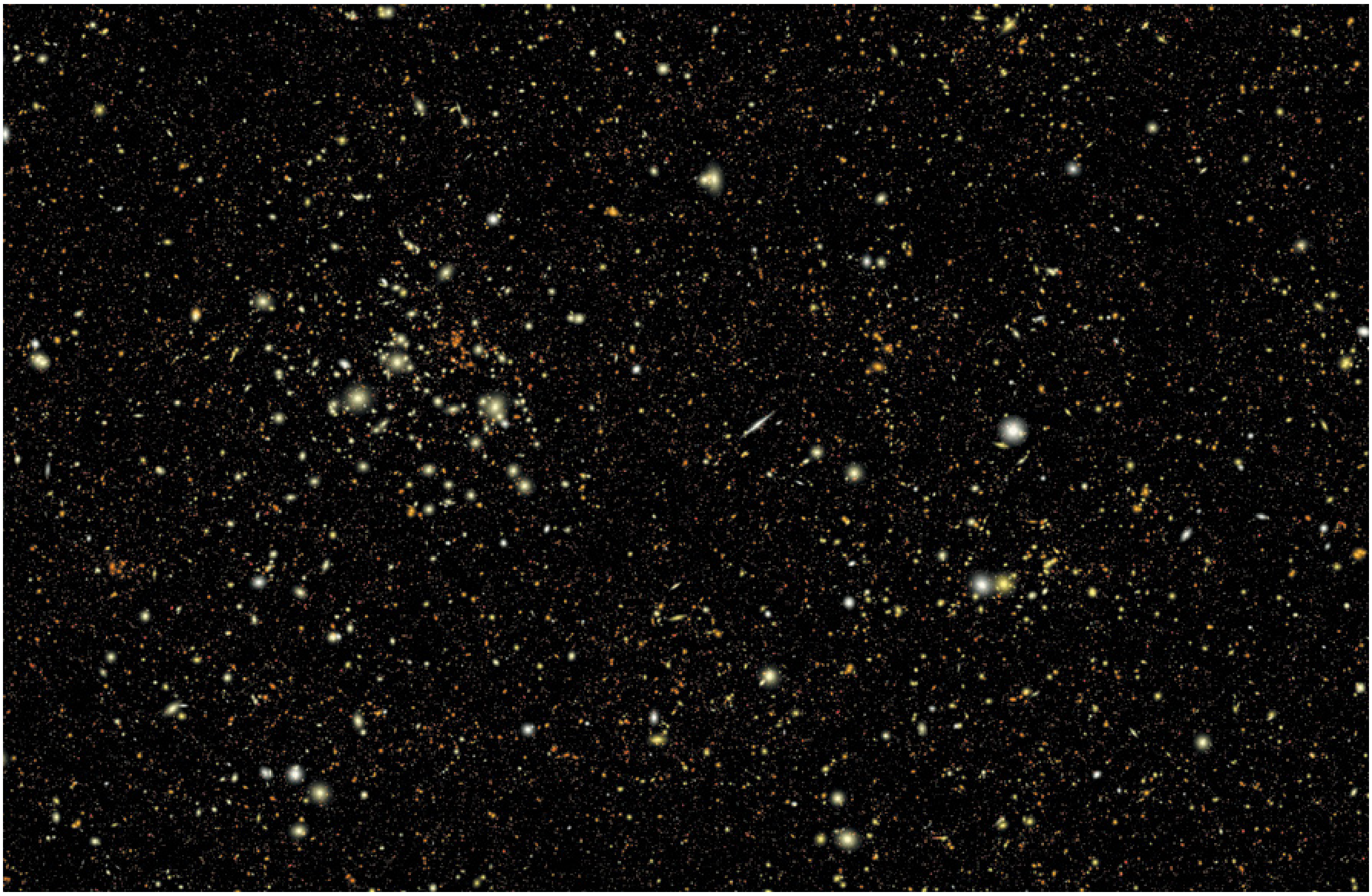

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M. Troxel and Caltech-IPAC/R. Hurt

A simulated view of hundreds of thousands of galaxies offers a preview of what the upcoming Nancy Grace Roman Space Telescope will see. The project will study the nature of the dark energy pulling apart the universe.

ON THE COVER
Not long ago a global drawdown of nuclear weapons seemed, if not likely, at least possible. Times have changed. The U.S. is modernizing its nuclear arsenal, with plans to make new warheads for the first time since the end of the cold war. The military says the project will make us all safer. Critics say the program is dangerous beyond belief.

Illustration by Taylor Callery.

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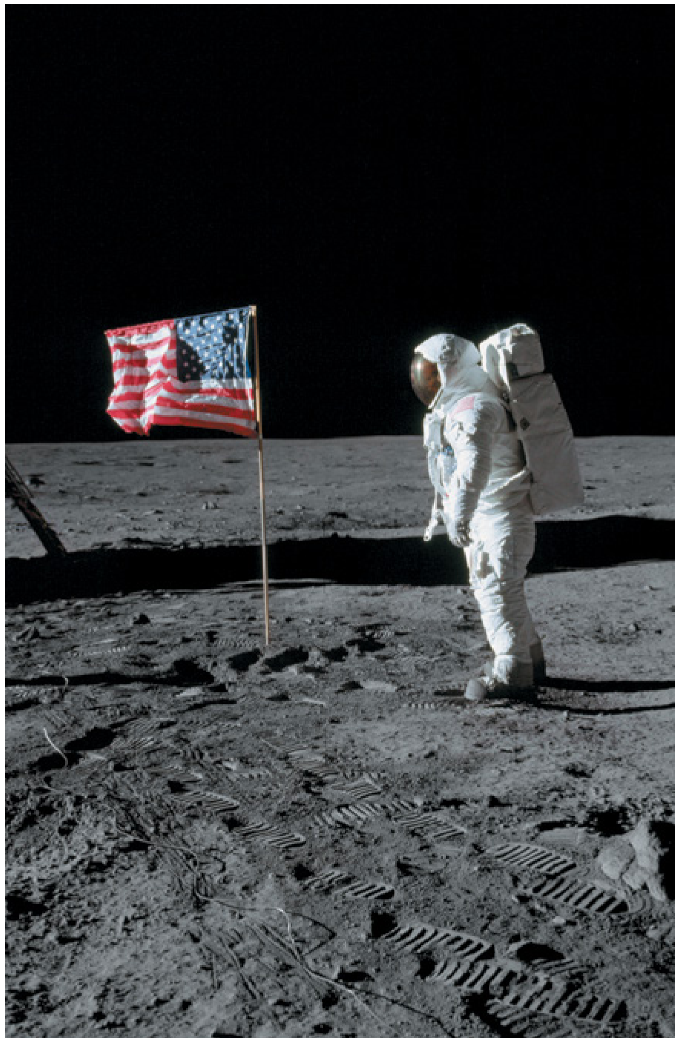

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NASA

New Nukes

WE'RE IN THE EARLY STAGES of a new nuclear arms race. It has not gotten much popular attention yet, and we at *Scientific American* hope that our special report starting on page 22 will help people think through the dangers and implications of a $1.5-trillion (with a T) plan to build up the U.S. nuclear arsenal. Perhaps the most controversial part of the plan involves refurbishing the land-based missile system. Upgraded nuclear missiles will be planted in hundreds of silos across five states, where they will be potentially vulnerable to attack. As our editorial on page 72 points out, it's basically a "kick me" sign on the middle of the country.

The next decade is going to be a "boom time" for nuclear weapons, as a nonproliferation scholar tells journalist Abe Streep. Starting on page 24, Streep takes us to nuclear weapons sites across the U.S. to understand how the previous arms race shaped history and what future the new arms race might bring.

Plutonium is a weird and scary substance. Writer Sarah Scoles is one of the few people without a high-security clearance to tour the tightly guarded Los Alamos National Laboratory facility in New Mexico where plutonium is being shaped into new pits to trigger fission and then fusion reactions that, as she says in a story beginning on page 39, make nuclear weapons nuclear.

Nuclear weapons on alert in silos across the western U.S. have a perverse strategic purpose: to serve as a "great sponge" to soak up enemy missiles. Seriously. *Scientific American* published articles in 1976 and 1988 showing the potential fallout from an attack on these weapons fields. Now, on page 46, nuclear weapons expert Sébastien Philippe has used advanced modeling to create maps that illustrate how such contamination could cause millions of deaths.

As part of this package on our website, we have a 20-minute documentary called *Fallout* by filmmakers Duy Linh Tu, Sebastian Tuinder and Nina Berman (Berman's photos accompany the print stories) that traces the legacy of nuclear weapons in the American West. In a five-part podcast series, *Missiles on the Rez,* host Ella Weber, who is a member of the Mandan, Hidatsa and Arikara Nation, takes listeners on a personal journey as she discovers more about her community and its long relationship with nuclear weapons.

Up to 20 percent of people in the U.S. have dyslexia, a condition that makes it difficult to learn to read. Many young people who are struggling with it don't get a proper diagnosis or receive the academic help they need, often because of an outdated testing method that has been recognized as flawed for years but is still used in many school systems. The "discrepancy model" compares a student's reading skills with their IQ (itself a flawed test) and diagnoses dyslexia only if there is a mismatch. Journalist Sarah Carr shows how this and similar models have failed too many children, and she offers hope that many more children can be taught to read. Turn to page 56.

Dark energy is one of the strangest discoveries in the history of science. Twenty-five years ago two teams of researchers independently found that the universe is expanding, not contracting—and not just that, but the expansion is accelerating. Dark energy, whatever that is, is causing the expansion, and we have learned a lot about it (but nowhere near enough) since it was named. Author Richard Panek on page 62 shares the ingenious ways that physicists have been trying to understand dark energy and the fate of our universe.

Laura Helmuth
is editor in chief
of *Scientific American.*

ABE STREEP BOOM TIMES, *PAGE 24*
Living in New Mexico, you “cannot avoid Los Alamos,” says journalist Abe Streep. Los Alamos National Laboratory, the birthplace of the atomic bomb, sits perched above the Rio Grande valley. It is still cleaning up from the Manhattan Project—even as it ramps up production of new plutonium cores to replace the U.S.’s arsenal of nuclear warheads.

For this issue’s report, Streep road-tripped through the American West to follow the ripple effects of plutonium “from cradle to grave.” As part of the journey, which included waste-disposal sites in the sands of the Permian Basin and underground missile storage next to farms in Wyoming, he went to the site of the former Rocky Flats Plant in Colorado. It manufactured plutonium pits until it was closed for safety violations in the late 1980s. Today a wildlife refuge stands on the contaminated ground, abutting gleaming new housing developments. The story of these communities’ nuclear past, present and future is a layered one, full of economic and cultural tensions. “The job of the story,” Streep says, “was to try to think about that in a complicated way.”

NINA BERMAN THE NEW NUCLEAR AGE, *PAGE 22*
A New York–based multimedia journalist, Nina Berman (*above*) has often covered environmental contamination by the U.S. military. But until recently, “like most Americans, I was pretty much unaware that we’re going to recapitalize our entire nuclear arsenal,” she says. “It really slipped underneath the radar.” Her initial work on the subject evolved into part of this issue’s special report on the new nuclear age, which explores the consequences of a massive—yet quiet—reinvestment in mutually assured destruction. “It’s kind of like, well, we’ve always had [nuclear missiles], so why not keep having them? What’s the big deal?” Berman says. “The choices we’ve been offered are so limited.”

As a photographer and researcher for “Boom Times” (*page 24*), she traveled across the U.S. to visit the communities directly impacted by nuclear weapons. In Nebraska and North Dakota, she was struck by the unsettling eeriness of the missile silos: “You know that there’s something lethal in the ground. But you also see strange, banal things like porta-potties out in front.” Berman loves movies and will often have a film in her mind while shooting an assignment. For this project, she says, “the whole thing is *Dr. Strangelove.”*

“I was pretty much unaware that we’re going to recapitalize our entire nuclear arsenal.”
—Nina Berman

SÉBASTIEN PHILIPPE SACRIFICE ZONES, *PAGE 46*
By his mid-20s Sébastien Philippe was an engineer responsible for analyzing the safety of French sea-launched nuclear ballistic missiles, poring over thousands of pages of data and documents to spot inconsistencies and potentially dangerous problems. He soon decided to pivot to nuclear weapons policy research and applied for a Ph.D. program at Princeton University. In a grim coincidence, his interview was on March 11, 2011—the day a massive tsunami blacked out Fukushima’s nuclear power facility. The subsequent explosion broadened how Philippe thought about nuclear weapons safety and risks, which he now studies as a research scientist at Princeton.

For this issue’s report, Philippe modeled the fallout from potential explosions of the nuclear weapons stored in the heartland of the U.S. The results were sickening, particularly the map of the worst-case scenario. “You have good days, and you have bad days. And that day was really bad,” he says. Especially shocking was the impact beyond the U.S. on swaths of Canada and Mexico. Even after decades in the field, “I had never seen [maps like] that before.”

MELINDA BECK MISDIAGNOSING DYSLEXIA, *PAGE 56*
When she was diagnosed with dyslexia in third grade, Melinda Beck decided she would choose a career where she didn’t have to read or write. “I told myself I could be a ballerina, or I could be an artist. And I’m not that flexible, so I think I’m going to be an artist.” Beck’s career as an award-winning illustrator still involves plenty of e-mails, but technological features such as spell-check help her navigate a professional world not built to accommodate her brain.

For this issue’s feature on dyslexia, Beck depicts the pain and frustration she experiences when reading words on a page. If she doesn’t place a bookmark under each line, it feels like the lines come apart. “They all get tangled up,” she says. Distilling her own feelings into a piece of art was a unique challenge. “Usually as an illustrator, we tell other people’s stories.” But the personal nature of the project allowed Beck to come at the story with the richness of “a lifetime of unintended research.”

July/August 2023

WANDERING STAR

Phil Plait's article "Our Sun Was Born Far, Far from Here" [The Universe] was informative as to how our nascent Sol might have formed, and its anthropomorphic analogy of the sun having far-distant and widespread "siblings" was quaint. But to use this analogy, young stars do not spontaneously go wandering off like runaway adolescents. It would have been helpful for the article to include some discussion of how these sibling stars might have become so widely dispersed in our galaxy.
CHARLES WEST *SALEM, VA.*

PLAIT REPLIES: *Stellar clusters are held together by the combined gravity of all the stars in them. Over time, as the stars move around and interact gravitationally, more massive stars fall to the center while lower-mass ones move outward. As they move farther out, these lower-mass stars are held less tightly by the cluster. The overall gravity of the galaxy can then pull them out. Also, stars in a cluster are packed rather tightly together. So it's common for there to be gravitational interactions among stars, with lower-mass stars like our sun getting flung out after a close encounter.*

PAVEMENT PLANNING

"Dangerous Discomfort," by Terri Adams-Fuller, discusses extreme warming in urban areas caused by the "heat island" effect. There was a relatively reflective surface on the paved street where I live until someone decided the entire neighborhood needed to be retarred. Now it's all black and hot. The question is how to get policy makers to prioritize strategies to make cities cool.

Dark roofs compound the problem. I've reroofed my house with light-colored, highly reflective shingles, and the reduction in air-conditioning is considerable.
PETER A. LAWRENCE *SAN JOSE, CALIF.*

BAD BRAIN SYNCHRONY

I was fascinated to read "Synchronized Minds," Lydia Denworth's article about how humans' brain waves synchronize when we interact. The article focuses on positive effects of this brain synchrony, but I wonder whether it also comes into play in things such as groupthink and mob behavior. If everyone's brain is working the same way, does that limit what the group sees as possible options?
FORREST STEVENS *PRINCETON, IDAHO*

DENWORTH REPLIES: *This letter raises an interesting question that researchers are beginning to address. One 2021 study in the* Proceedings of the National Academy of Sciences USA *found that shared political ideology led to increased neural synchrony when participants viewed partisan debates. But the effect was moderated by a willingness to tolerate uncertainty. And in another study of perceived in-groups and out-groups in* NeuroImage *that year, more synchrony was seen among members of the same group (in this case, among Israelis or among Palestinians) than across groups.*

WELCOME INVADERS

"Parrot Invasions," by Ryan F. Mandelbaum, couldn't be more timely here in San Francisco. The city just picked our local "wild" parrot as its official animal, giving the bird a narrow win over the sea lion. The article describes such birds as "innovators, problem solvers, socializers and survivors," which is also a very apt description of San Franciscans.
BRIAN VEIT *SAN FRANCISCO*

DOTTING YOUR EYES

"Seeing Numbers," by Nora Bradford [Advances], includes an illustration that presents two groups of dots. The caption poses the question "Which has 50 dots, and which has 51?" You left us to guess the answer or count the tiny dots for ourselves. Readers of *Scientific American,* like insects, are far more cognitively complex than previously thought and can feel frustration and pain. Henceforth, please treat us with greater consideration.
J. C. SMITH *CROZET, VA.*

FUSION OF POSSIBILITIES

Thank you for "Star Power" [June], Philip Ball's fascinating, hype-free article about the future of nuclear fusion power. One question remains: How do engineers get the heat out of the tokamak, the most popular fusion-reactor design? A conventional power plant does this by pumping high-pressure water through a heat exchanger, which turns it into steam, which drives a turbine. This key step in the power-generating process—generating the power—is not addressed in the article.

Ball notes that ITER will be the first fusion reactor that will demonstrate continuous energy output at a power plant's scale. How will it boil enough water to drive a 200-megawatt turbine when the exhaust from its fire is 150 million kelvins?
PETER B. WILSON *PHOENIX, ARIZ.*

Ball describes underway fusion-reactor projects that are, overall, big and expensive, such as ITER in France, which has a 23,000-metric-ton research reactor and will likely cost more than $20 billion.

Lockheed Martin's Skunk Works division is developing compact fusion reactors small enough to power jet flights and other aircraft, ships and small cities. Enormous fusion projects often are abandoned because of unanticipated delays and cost overruns spiraling out of control. The compact fusion model is likely to be cheaper and faster to develop

"The question is how to get policy makers to prioritize strategies to make cities cool."
PETER A. LAWRENCE *SAN JOSE, CALIF.*

because such test reactors can be built in months. Smaller approaches to fusion may be more likely to succeed in the long run and to result in a workable device much sooner than the gargantuan projects.
STEVEN BRENNER *UNIVERSITY CITY, MO.*

BALL REPLIES: *Regarding Wilson's question: For tokamaks, heat exchange is most likely to be done via water cooling. That is the plan for ITER. It is true that the challenge of drawing off heat from a plasma at many millions of kelvins to heat water to perhaps a couple of hundred degrees Celsius is significant. But the principles of this engineering problem have been figured out. For EUROfusion's DEMOnstration Power Plant (DEMO) prototype, the current plan seems to be to use a lead-lithium alloy surrounding the fusion chamber as an intermediate heat-exchange blanket. The lithium will also absorb the neutrons emitted by fusion and be converted into tritium fuel—it is a so-called breeding blanket.*

To answer Brenner: I don't think the development of larger versus smaller reactors is generally regarded as either/or. As I say in my article, ITER is not intended as a commercial reactor or even a prototype for one; it is being developed to solve engineering challenges. Smaller reactors such as DEMO and the U.K.'s Spherical Tokamak for Energy Production (STEP) will serve as prototypes for actual plant-scale devices. Even smaller ones like those being developed by some private companies might also become viable: some of them have discussed devices of around 100 megawatts, small and compact enough to be used for container ships.

ERRATA

In "The Most Boring Number," by Manon Bischoff [June], the chart in the box "A Gap of Judgment" depicted incorrect numbers in the *y* axis. The corrected illustration can be seen at www.scientificamerican.com/article/the-most-boring-number-in-the-world-is

"A Stratospheric Gamble," by Douglas Fox [October], should have described the contemplation of a "scenario in which individual countries . . . begin injecting aerosols unilaterally" as separate from comments made by Katharine Ricke.

ADVANCES

NEUROSCIENCE

Star Cells

Neurons are not the only brain cells that send signals

Thom Leach/Science Source

OUR THOUGHTS and feelings arise from networks of neurons, brain cells that send signals using chemicals called neurotransmitters. But neurons aren't alone. They're supported by other cells called glia (Greek for "glue"), which were once thought to hold nerve tissue together. Today glia are known to help regulate metabolism, protect neurons and clean up cellular waste—critical but unglamorous roles.

Now, however, neuroscientists have discovered a type of "hybrid" glia that sends signals using glutamate, the brain's most common neurotransmitter. These findings, published in *Nature*, breach the rigid divide between signaling neurons and supportive glia.

"I hope it's a boost for the field to move forward, to maybe begin studying why certain [brain] circuits have this input and others don't," says study co-author Andrea Volterra, a neuroscientist at the University of Lausanne in Switzerland. Around 30 years ago researchers began reporting that star-shaped glia called astrocytes could communicate with neurons. The idea was controversial, and further research produced contradictory results. To resolve the debate, Volterra and his team analyzed existing data from mouse brains. These data were gathered using a technique called single-cell RNA sequencing, which lets researchers catalog individual cells' molecular profiles instead of averaging them in a bulk tissue sample. Of nine types of astrocytes they found in the hippocampus—a key memory region—one had the cellular machinery required to send glutamate signals.

The small numbers of these cells, present only in certain regions, may explain why earlier research missed them. "It's quite convincing," says neuroscientist Nicola Hamilton-Whitaker of King's College London, who was not involved in the study. "The reason some people may not have seen these specialized functions is they were studying different astrocytes."

Using a technique that visualizes glutamate, the researchers observed the cells in action in live mice. They found that blocking their signaling impaired the mice's memory performance. Further mouse experiments suggested these cells might play a role in epilepsy and Parkinson's disease.

MACHINE LEARNING MAPS SMELLY MOLECULES P. 16
ANCIENT BRICK GETS GENETIC TESTING P. 18
PLASTIC WASTE ZAPPED INTO CLEAN FUEL P. 18


Astrocytes, a type of glial cell

Analysis of human RNA databases indicates the same cells may exist in us, but they have not been directly observed.

"People modeling brain circuits never consider these other cells," Hamilton-Whitaker says. "Now we'll all have to agree they're part of the circuit and need to be included to understand how circuits work."

First, neuroscientists must map where in the brain these special cells can be found. Because Volterra's team located them in structures associated with memory, the researchers plan to examine data from people with Alzheimer's disease to see whether, and how, their signaling astrocytes are altered. "We know they're located in memory circuits, so the next question is, What happens in dementia?" Volterra says. "If these cells are modified, they become a new target" for research.

—Simon Makin

Rocky Start

A plate tectonics mystery

GEOLOGY As giant slabs of Earth's crust collide in ultraslow motion, they create mountains, trigger earthquakes and forge new rocks. No one knows how or when this fundamental process, called plate tectonics, began. But an experimental study published in *Nature Geoscience* suggests early plate tectonics created the oldest rocks on Earth, which are about four billion years old—just short of the planet's age of 4.5 billion years.

"Everyone talks about, 'When did plate tectonics start?'" says study author Alan Hastie, a University of Edinburgh igneous petrologist. "I think that's the wrong question. It's basically always been."

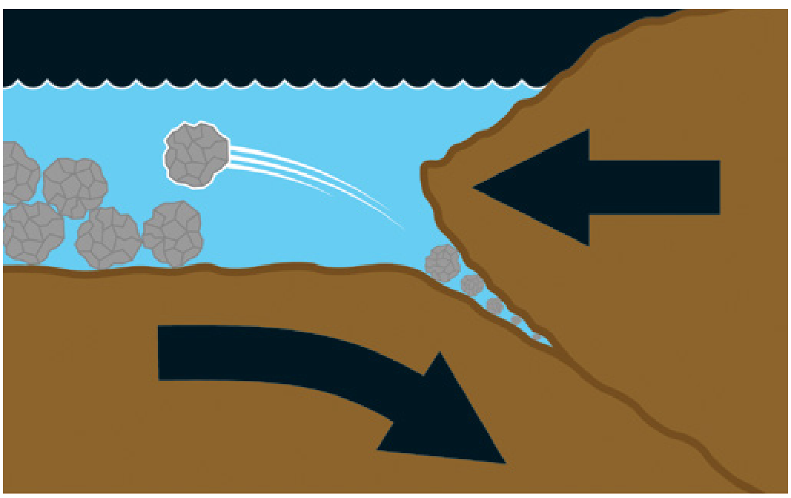
But Earth was a warmer, more gooey planet when its magma ocean first solidified, and its brand-new crust would seem more likely to bend than to break into plates. Scientists who use computer models to reconstruct this early environment tend to think plate tectonics began three billion years ago or less, because simulations struggle to show how the process could have started before that. Field geologists, however, often point to four-billion-year-old rocks in places such as Canada and Australia as evidence of an earlier start. These ancient rocks appear to have been made by subduction, when two plates collide to thrust one of them deep into Earth's mantle.

Hastie and his colleagues set out to test whether these oldest rocks could have instead been created at shallower, nonsubduction depths. They took samples from oceanic crust in the southwestern Pacific, which has a composition similar to Earth's first continental crust, and subjected them to high pressures and temperatures to simulate the environment in which they might have formed without subduction, in the upper 50 kilometers of the crust.

The researchers found that this environment couldn't produce samples with the same mineral makeup as the four-billion-year-old rocks. Rocks formed under different pressures and temperatures are composed of different minerals, so this mismatch between the new and ancient samples indicated that the ancient rocks had formed farther—more than 50 kilometers—down. Subduction is the only known process that could push so deep.

"You need to have formed these rocks under much higher pressure—and to get that pressure, the easiest mechanism is subduction," says Nadja Drabon, a geologist at Harvard University, who was not involved in the new study.

Subduction on early Earth may have been less dramatic than today, with warmer crust less likely to dive as deep into the mantle as modern tectonic plates do, says study co-author Sally Law, a postdoctoral researcher at the University of Edinburgh. This raises new questions about how early Earth's geologic restlessness might have become self-perpetuating, Drabon says. "The big question is, How well would [Earth] be able to sustain a plate tectonic process?" she asks. "That's something we need to do a whole lot more work on." *—Stephanie Pappas*



SOCIAL SCIENCES

Turning the Page

Characters in influential children's books are still mostly white

CHILDREN'S LITERATURE has become far more diverse in the past decade, helping more kids than ever to see themselves in their favorite books. Of the thousands of kids' and teens' books reviewed in a 2022 analysis, about 45 percent had a nonwhite author, illustrator or compiler, up from 8 percent in 2014. "There are just so many more choices of books [reflecting] the multifaceted complexity of individual lives," says Tessa Michaelson Schmidt, director of the Cooperative Children's Book Center at the University of Wisconsin–Madison.

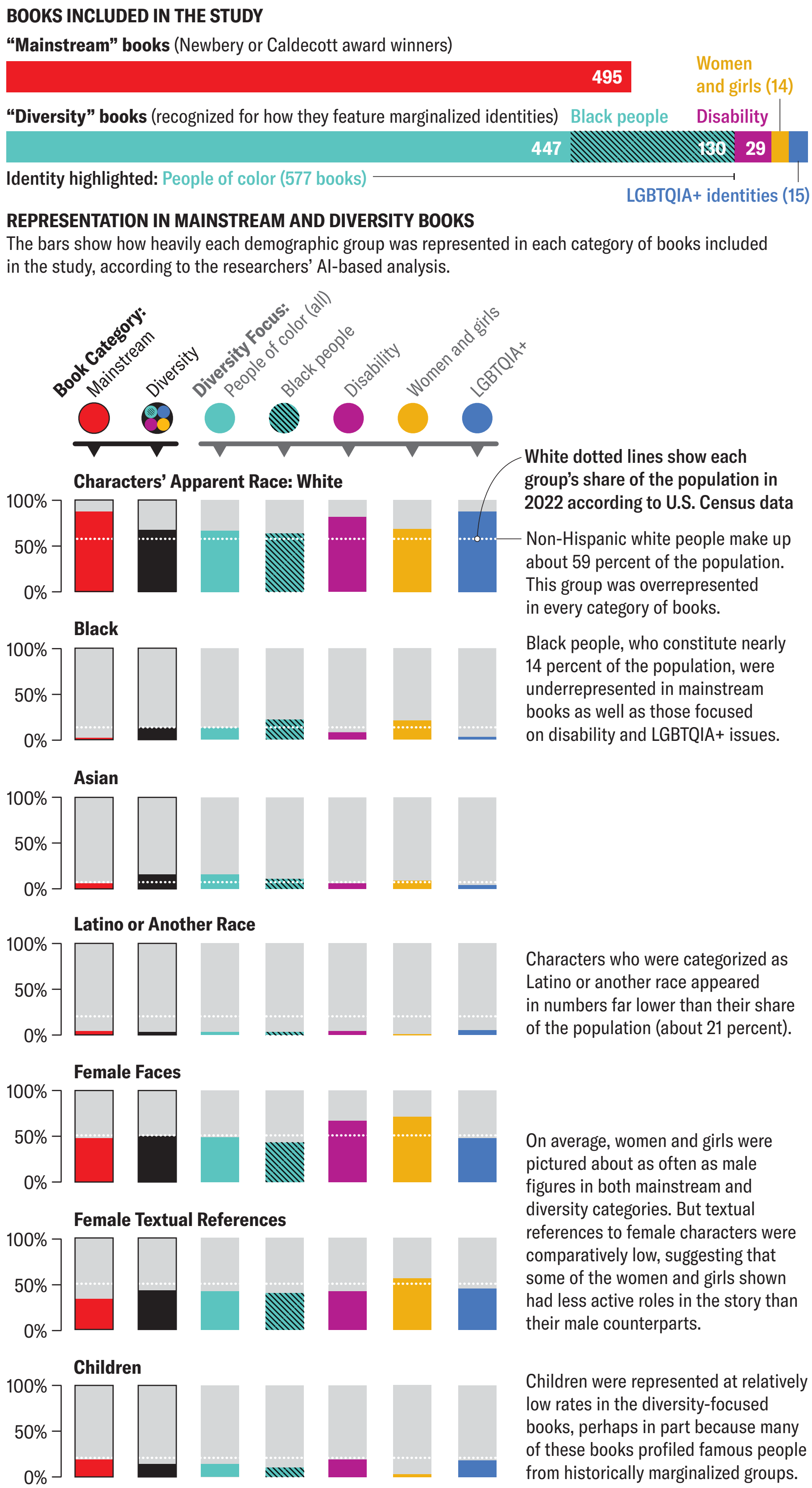
But white males remain overrepresented in the most influential children's stories, the authors of a recent study concluded. The research, published in the *Quarterly Journal of Economics*, examined the winners and honorees of the Newbery and Caldecott medals—widely considered the most prestigious prizes in kids' literature—and the recipients of 17 awards for diversity. University of Chicago social scientist Anjali Adukia and her colleagues scanned 1,130 of these award-winning books, covering more than 162,000 pages, and used an artificial-intelligence program trained to detect faces and determine the age, race and gender of each pictured character.

Machine learning let the researchers pick up on details they may have missed if they had combed through the books by hand. For example, on average, youngsters were depicted with lighter skin than adults of the same race. And female characters appeared more often in images than in text, which "suggests more symbolic inclusion ... rather than substantive inclusion," according to the study's authors. They also found that the vast majority of famous people mentioned in Newbery- and Caldecott-winning books are white.

The results come amid a nationwide cultural clash, with diversity campaigns running alongside attempts to ban books that address aspects of race and sexual identity. But kids crave exposure to stories about people like them, which build up their feelings of self-worth and help them maintain an interest in reading, says Caroline Tung Richmond, an author of young adult fiction and executive director of the nonprofit organization We Need Diverse Books. At the same time, she says, young people benefit from stories that allow them "to see into a different culture or identity and build empathy." *—Jesse Greenspan*

Illustrations by Thomas Fuchs

Quantifying Diversity in 1,130 Children's Books



Source: "What We Teach about Race and Gender: Representation in Images and Text of Children's Books," by Anjali Adukia et al., in *Quarterly Journal of Economics*, Vol. 138; 2023 (data)

Graphic by Amanda Montañez

CHEMISTRY

Nanoscale Bulldozer

Scientists discover a one-molecule motor that hops in straight lines

IN A BASEMENT room at Austria's University of Graz sits a jumble of steel tanks and ice-encrusted tubes. The contraption, a scanning tunneling microscope, can snap pictures of individual atoms and molecules. It's so sensitive that it works best at night, when nobody's around to walk or talk or otherwise rattle the building.

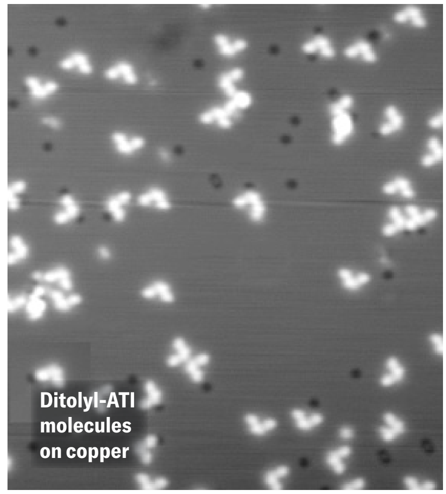
A computer monitor beside the machine shows images of tiny, heart-shaped blobs arrayed over a copper surface. The "hearts" are individual molecules: ditolyl-ATI molecules, to be precise. Earlier this year Grant Simpson, a chemist in the microscopy laboratory, had been playing around with them, hoping they could be coaxed to act like minuscule mechanical switches.

What he found instead was far more intriguing. When excited with an electrified microscope tip, the molecules jumped—but they didn't hop around willy-nilly. "Somehow," Simpson says, "I'd come to the realization, slowly, that they're only moving in one direction."

The hopping hearts are an entirely new kind of molecular nanomotor—a tiny machine that expends energy to move purposefully against the entropic tides that constantly pull the small-scale world into random, useless motion. Some human-made nanomotors can spin in place, but few can reliably move from point A to point B. The mechanical magic of the new motor, described recently in *Nature,* comes from the interaction between the molecule and the copper surface it moves along—as if a train engine had parts both in the car and embedded in the track below.

It's a small but significant step toward the dream of a nanotechnology that can build things nature's way: bottom-up, atom by atom. "If we build a chair, we take a tree, and we cut it down," says physicist Leonhard Grill, Simpson's colleague at the University of Graz. "Nature does it the opposite way. Nature grows the tree." Researchers developing miniature machines imagine using them to create novel materials, to supercharge industrial catalysis and to manipulate biological tissues with the agility of real enzymes.

"Miniaturization has always driven advances in technology," says chemist David Leigh of the University of Manchester. But the problem with nanotechnology, he explains, is that the familiar mechanics of the "big world" simply don't work on the molecular level. At such tiny scales, randomness rules. If properties such as temperature, energy and pressure are held steady, then small-scale processes—including chemical reactions or the movements of particles—are equally likely to happen in every direction. Moving from A to B at the nanoscale is like rolling a die and taking



Ditolyl-ATI molecules on copper

From "Adsorbate Motors for Unidirectional Translation and Transport," by Grant J. Simpson et al., in *Nature,* Vol. 621; September 6, 2023

steps forward, backward or sideways depending on the result. "You can't use Newtonian mechanics" in nanotechnology, Leigh says. "That basically rules out all the engineering processes that we've built up as civilizations over the past 5,000 years."

So why do scientists think it should be possible to develop nanoscale machinery at all? Leigh says the answer is that there's already a mature and working example out there, "and it's called biology." The intricate natural enzymes that flap a bacterium's flagella, twitch an animal's muscles and synthesize chemical energy in a cell's mitochondria are all molecular machines.

In 1999 scientists synthesized the first true molecular nanomotor, a light-powered rotary motor that was later recognized with a Nobel Prize in Chemistry. Since then, scientists have developed many more types of motors with different capabilities. Uni-

Mine Spotting

An AI model could help clear land mines

AI

Finding and removing land mines is an excruciatingly slow process. Human deminers scour contaminated ground inch by inch with handheld metal detectors, waiting for the telltale beep of a magnetic anomaly. Although trained dogs are sometimes used, metal detectors have remained the go-to clearance method since the end of World War II.

"There's a very long period where there hasn't been much innovation in the field," says Jasper Baur, a Ph.D. student in volcanology and remote sensing at Columbia University. Baur and his collaborators at Safe Pro Group, a manufacturer of personal protective gear, have been developing a drone-based machine-learning technology to make demining safer and faster than with traditional methods.

The idea is deceptively simple: A drone flies over an area thought to be mined, collecting a large volume of images. Baur's algorithm, trained on the visual characteristics of 70 types of land mines, cluster munitions, and other unexploded ordnance, processes the images into a map, with resolution down to a fraction of an inch. The model can then recognize and map explosives more quickly and accurately than a human reviewing the same images. "In a matter of minutes you'll have a map plotted out with where all the land-mine detections are," Baur says.

With a reported detection rate of about 90 percent, the drones are meant to augment traditional methods, not replace them. "It's less comprehensive because you're not going through inch by inch," Baur says. But the approach can reveal potential dangers and versity of Groningen chemist Nathalie Katsonis and her colleagues recently stuck trillions of nanorotors together and synced them up to physically move a macroscopic polymer. And Leigh and his colleagues have developed rotary nanomotors that, like biological enzymes, move by harnessing energy from chemical reactions catalyzed by the motor itself.

But rotary motors spin in place; molecular motors that move in straight lines, like trains on tracks, have proved a greater challenge to build. Some researchers have synthesized ring-shaped molecules that can rotate and slide along dumbbell-shaped scaffolds. Then there are DNA "walkers," which have legs and move by taking steps, like some biological motor proteins. But DNA walkers are relatively hefty (not strictly "nano," Leigh says) and can take only a handful of strides along carefully prefabricated nucleic acid tracks. The new heart-shaped motor, though, is just a few nanometers across and will keep hopping along its track of copper atoms as long as the surface isn't interrupted.

Simpson and Grill discovered the motor mostly by accident—it was "pure serendipity," Grill says. The scientists were initially intrigued by how the ditolyl-ATI molecule tosses one of its hydrogen atoms back and forth between its two nitrogen atoms, a behavior the scientists thought could make it useful as a nanoscale switch. After years of work, Simpson tried depositing the molecules on a particular kind of copper surface in which the atoms are arranged in linear rows. To his surprise, a jolt of electricity sent the hearts hopping along the copper tracks. The researchers then confirmed that the molecules move in just one direction and can even push along other particles like nanoscale bulldozers.

This new motor is an "energy ratchet," says Katsonis, who was not involved in the study. It uses energy—here a jolt of electricity—to switch between two states, each with a different set of energetic possibilities. Zapping the molecule makes it lurch into its more excited state, in which moving forward along the copper rail is favorable. When the molecule falls back down to its original, unexcited state, it jumps exactly one step forward along the track.

"In my opinion, it's interesting for two reasons," Katsonis says. First, the molecules interface with something bigger than themselves, in this case a surface. Second, they move in a line along an atomic track—the key to mastering directional motion at the nanoscale, she says. After all, biology's many linear molecular motors typically strut along scaffolds to travel in the right direction.

"This is really nice because it's just moving one-dimensionally, directionally, in a very minimalist system," Leigh says. The new energy ratchet probably won't propel a nanobot or assemble a tree atom by atom anytime soon. But it can be easily studied with scanning tunneling microscopes, making it a perfect test system for future experiments with energy ratchets, tracks and directional motion—and Katsonis and Leigh say that's a big hop in the right direction.

—Elise Cutts

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can cover more ground than manual efforts.

Baur and his team have visited Ukraine to test the technology multiple times since the start of the war there. They hope their work can speed up a demining process that, using current resources, could take more than 750 years. By some estimates, Ukraine has about 67,000 square miles (an area roughly the size of Florida) that could harbor mines and other explosives. With the new system, "you can scan wide areas of land and try to figure out where the highest density of contamination is" before sending in humans to defuse the mines, Baur says.

For now the AI can detect only surface-level explosives, not deeply buried ones or those covered by vegetation. Baur's nonprofit organization, the Demining Research Community, is testing ways to look deeper by using thermal imaging and ground-penetrating radar. It is also developing a model that can rate the AI's level of confidence in its mine-detection results based on the amount of vegetation present.

Milan Bajić, an expert in remote sensing who has been involved in demining efforts in Croatia, says the approach is a valuable addition to the demining tool kit. "There is no silver bullet of technology," he says, "but combining different technologies can be more successful than any of them."

—Lori Youmshajekian

PERCEPTION

What's That Smell?

AI predicts how unknown chemicals will smell to humans

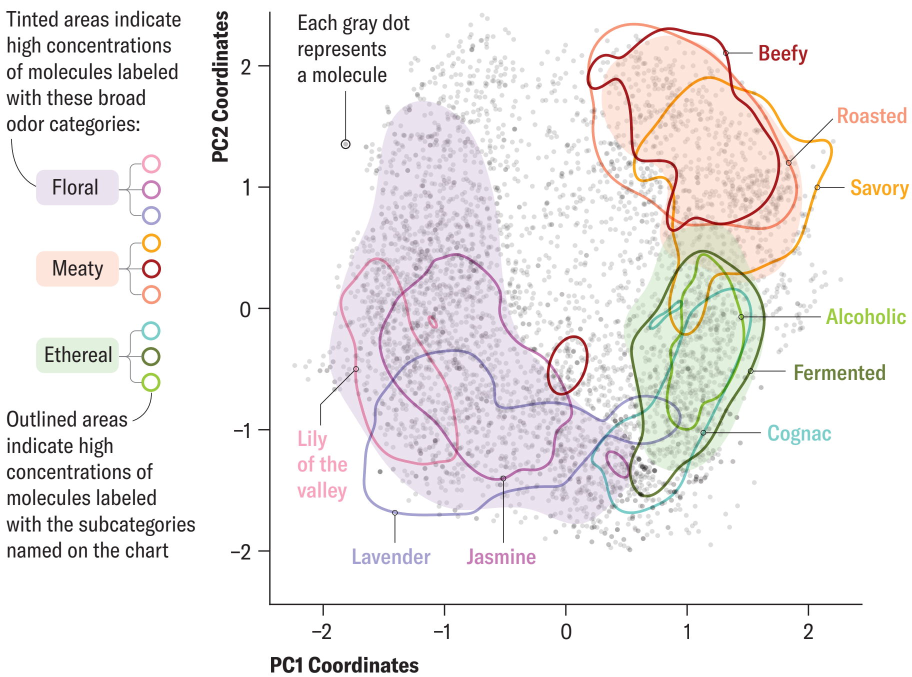
TO A HUMAN NOSE, hydrogen sulfide smells like rotten eggs, geranyl acetate like roses. But the problem of guessing how a new chemical will smell without having someone sniff it has long stumped food scientists, perfumers and neuroscientists alike.

Now, in a study published in *Science*, researchers describe a machine-learning model that does this job. The model, called the Principal Odor Map, predicted smells for 500,000 molecules that have never been synthesized—a task that would take a human 70 years. "Our bandwidth for profiling molecules is orders of magnitude faster," says Michigan State University food scientist Emily Mayhew, who co-led the study.

Principal Odor Map

Scientists assembled a data set of about 5,000 molecules, each described by various odor "labels" and structural features, resulting in a principal odor map encompassing 256 dimensions.

To create this chart, researchers compressed the 256-dimensional data into two dimensions: principal component 1 (**PC1**, shown on the *x* axis) and principal component 2 (**PC2**, shown on the *y* axis). Together, PC1 and PC2 capture 28 percent of the information contained in the full data set.



Source: Modified version of a chart from "A Principal Odor Map Unifies Diverse Tasks in Olfactory Perception," by Brian K. Lee et al., in *Science*, Vol. 381; September 1, 2023. Reproduced with permission.

Into the Deep When did fish first populate the deepest seas?

EVOLUTION

The strange life-forms lurking in Earth's deepest seas may seem primordial, as if they are as old as the oceans themselves. But the truth is that these fish and other animals took hundreds of millions of years to adapt to the pressure, cold and darkness of the depths, and a recent study helps pinpoint vertebrates' entry into this inky realm. The rarity of deep-sea fossils had previously left paleontologists with only a patchy understanding of life in the ancient deep. Now fossilized feeding traces created by hungry fish, described in the *Proceedings of the National Academy of Sciences USA*, indicate they were swimming in the deep seas by 130 million years ago.

The telltale fossils were first discovered a decade ago in Italy's Palombini Shale Formation, which once lay roughly 6,500 feet below the surface of the Cretaceous seas. These fossils didn't preserve the ancient fish themselves but rather recorded their behavior: the fish left behind a variety of pits, scrapes and sinuous trails in the sediments on the ocean floor.

No one knew what to make of these markings at first. "It took more than 10 years to realize the true nature of the trace fossils," says Andrea Baucon, a paleontologist at the University of Genoa. But after he observed modern Mediterranean fish creating similar structures, he says, "a light went on in my head." By studying the behavior of living fish, Baucon and his colleagues identified what probably created the ancient marks. The pits, for example, appear to have been made by fish that could jet water at the sediment to reveal hiding prey. The distinctive two-lobed scrapes were created by fish mouthing at the bottom to catch worms, and the S-shaped trails were created by a fish flicking its tail back and forth as it swam just above the seafloor. The results suggest that several fish species were living in deep waters and hunting for squishy prey by the Early Cretaceous period—37 million years earlier than indicated by previous fossil evidence of deep-sea vertebrates.

"The study is a superb example of how trace fossils can fill huge gaps in our understanding," says Emory University paleontologist Anthony Martin, who was not involved in the work.

This updated time line also hints at why fish adapted to such ocean extremes—they may have been following their wormlike invertebrate prey, Baucon says. These invertebrates spread because of changes in the

The color of light is defined by its wavelength, but there's no such simple relationship between a molecule's physical properties and its smell. A tiny structural tweak can drastically alter a molecule's odor; conversely, chemicals can smell similar even with different molecular structures. Earlier machine-learning models found associations between the chemical properties of known odorants (called chemoinformatics) and their smells, but predictive performance was limited.

In the new study, the researchers trained a neural network with 5,000 known odorants to emphasize 256 chemical features according to how much they affect a molecule's odor. Rather than using standard chemoinformatics, "they built their own," says Pablo Meyer Rojas, a computational biologist at IBM Research, who was not involved in the study. "They directly inferred the properties that are related to smell," he says—although how the model arrives at these predictions is too complex for a human to understand.

The model creates a giant map of odors, with each molecule's coordinates determined by its chemical properties. The model also predicts how each molecule will smell to a human, using 55 descriptive labels such as "grassy" or "woody." Remarkably, similar-smelling odorants appeared in clusters on the map—a feature prior odor maps couldn't achieve.

The team then compared the model's scent predictions with the judgments of 15 humans trained to describe new odorants. The model's predictions were as close as those of any human judge to the panel's average descriptions of the new scents. It could also predict an odor's intensity and how similar two molecules would smell—two things it was not explicitly designed to do. "That was a really cool surprise," Mayhew says.

The model's main limitation is that it can predict the odors of only single molecules; in the real world of perfumes and stinky trash bags, smells are almost always olfactory medleys. "Mixture perception is the next frontier," Mayhew says. The vast number of possible combinations makes predicting mixtures exponentially more difficult, but "the first step is understanding what each molecule smells like," Meyer Rojas says. *—Simon Makin*

A modern-day floor-dwelling fish (*Synodus intermedius*)

Wild Horizons/Universal Images Group via Getty Images

nutrients available in the ocean's depths. Deep-sea fish are carnivores, explains marine biologist Elizabeth Miller of the University of Oklahoma, who was not involved in the work. So "without something to eat [besides] each other, it's difficult to imagine fishes making a living in the deep sea." *—Riley Black*

NEWS AROUND THE WORLD

Quick Hits

By Lori Youmshajekian

CHINA Scientists discovered a previously unknown ninth species of pangolin by using contraband bits of the animals' natural armor confiscated in Hong Kong and Yunnan. The anteaterlike creatures are among the world's most trafficked animals, prized for meat and distinctive scales that some believe have medicinal properties.

NORWAY Melting ice in Norway has revealed a 4,000-year-old arrow, probably shot by a hunter pursuing reindeer. A team of glacial archaeologists, racing against climate change to save thawing artifacts, stumbled on the weapon in the Jotunheimen mountain range.

PACIFIC OCEAN A virus was discovered in the Mariana Trench almost 30,000 feet below the surface, the deepest a virus has been detected in the ocean. It infects bacteria found in deep-sea sediments and hydrothermal vents.

SATURN A collision between two moons a few hundred million years ago may have formed Saturn's most famous feature. Simulations show how the crash scattered rock and ice, with some of the debris forming the present-day rings.

SOUTH AFRICA A conservation group named African Parks will rewild 2,000 Southern White Rhinoceroses to protected areas across the continent over the next 10 years. The rhinos were purchased this year from a controversial captive-rhino breeding project.

TURKEY A previously unknown Indo-European language, spoken 3,000 years ago, was discovered on a clay tablet at Boğazköy-Hattusa, the site of the ancient capital of the Hittite Empire. Researchers believe the text documents a foreign religious ritual of interest to Hittite scribes.

ZAMBIA Two 476,000-year-old logs uncovered in a riverbed near Kalambo Falls, along with several wood tools, may be the oldest example to date of early humans using wood to build. The water-preserved logs were found fitted together with a carved notch.

For more details, visit www.ScientificAmerican.com/dec2023/advances

ARCHAEOLOGY

Building Knowledge

Scientists sequence DNA from a chunk of a Mesopotamian palace

THOUSANDS OF YEARS ago people building a palace molded mud from beside the Tigris River into a brick, scooping up parts of nearby plants in the process. Researchers recently managed to tease discernible plant DNA from that brick, providing a rare look at what was growing in Mesopotamia (now part of Iraq) nearly three millennia ago, according to a study published in *Scientific Reports*.

"We were amazed when it turned out that we were actually able to extract ancient DNA from this clay material," says co-author Sophie Lund Rasmussen, a biologist at Denmark's Aalborg University. "This paper is primarily a proof of concept; we wanted to share the idea and the method with the world."

Although scientists have extracted ancient DNA, or aDNA, from bones and lake sediments before, they hadn't thought to try the existing techniques on clay bricks. Many bricks used to build historic structures don't contain enough DNA for researchers to sequence, and bricks are often baked at high temperatures, which can degrade any plant DNA they might contain.

The newly studied brick, currently held by the National Museum of Denmark, had been sun-dried instead of fired. It was created between 883 and 859 B.C.E. and bears an inscription in the extinct Akkadian language reading "the property of the palace of Ashurnasirpal, King of Assyria." A crack in the center of the brick allowed researchers to take tiny, better-preserved samples from deep inside.

The researchers sequenced the plant aDNA in the brick and found evidence of 34 taxonomic groups, including cabbage, heather, birch and cultivated grasses—new clues as to what people in this "cradle of civilization" consumed. Larger aDNA fragments, along with advances in DNA sequencing and machine learning (used to help interpret sequences), could allow researchers to detect distinct plant species.

"Now the real work starts, and we have to develop the method further and make it even more precise," Rasmussen says. Her team's efforts show how aDNA can be found in materials not generally thought to contain enough genetic substance to sequence, she says.

Ancient DNA sequencing could be used with other techniques for analyzing plant material to paint a fuller picture of the past, says Mads Bakken Thastrup, an archaeobotanist at Denmark's Moesgaard Museum, who was not involved in the new study. Archaeobotanists currently examine evidence of ancient plant life by using chemical processes or imaging microscopes; extracting aDNA "could potentially be a valuable addition," Thastrup says. "The findings are still a bit 'low resolution,' and the method will likely need further development before we can identify the plants at the species level. When that becomes possible, it will be truly interesting." —*Susan Cosier*

Plastic Fuel

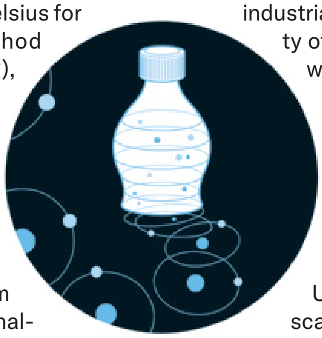
Waste plastic becomes hydrogen gas and a type of graphene

MATERIALS SCIENCE

Hydrogen gas is a carbon-free energy source that can be burned in place of fossil fuels. But its most common production method relies on methane, a potent greenhouse gas. Other known methods are costly and resource-intensive. Now researchers have found a cleaner—and, in theory, profitable—way to make hydrogen gas from waste plastic. The process also generates graphene, an extremely valuable, ultrathin carbon material used in products such as electronics, concrete and car parts.

This method could help keep heat-trapping carbon out of the atmosphere, says James Tour, a Rice University chemistry professor and senior author of a recent study on the topic, published in *Advanced Materials*.

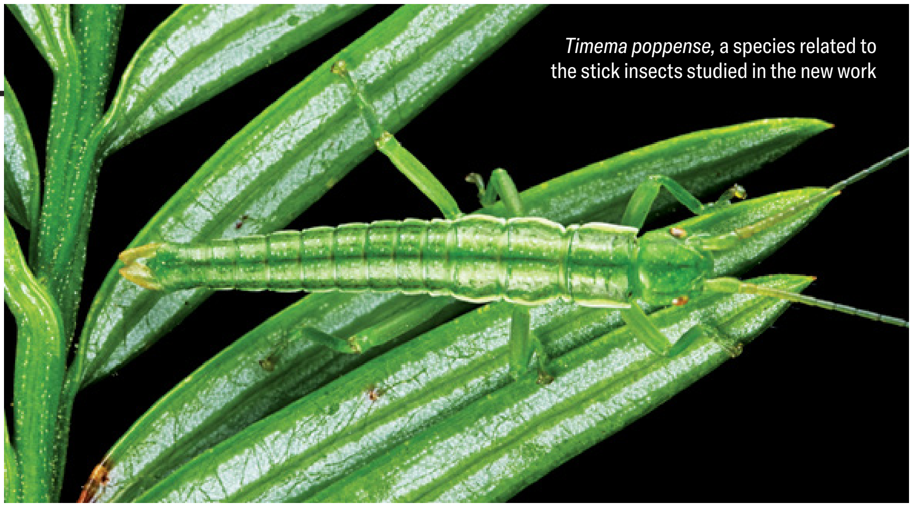
For a 2020 study, Tour and his team used a strong electric current to heat plastic to about 2,700 degrees Celsius for mere milliseconds (a method called flash Joule heating), which breaks down plastic's chemical bonds. This technique produced a type of graphene that has several atom-thin sheets of carbon lattices rather than the typical single layer. It also released a gas, but the team needed to conduct further analysis to confirm what this gas was. Now the researchers have found it was up to 94 percent pure hydrogen.



As part of the new study, the scientists did a life-cycle assessment of the process to compare it with other ways of producing the gas in terms of its cost and emissions. They found that flash Joule heating could generate 39 to 84 percent fewer greenhouse emissions than other hydrogen-production methods. It could also help pay for itself by yielding graphene—although the multilayer version is less in demand, and it's unclear what price it might sell for, says Juan Pablo Trelles, a professor of mechanical and industrial engineering at the University of Massachusetts Lowell, who was not involved with the study.

The hydrogen-generating technique works with mixed plastic waste and could also theoretically work for other carbon-based household garbage such as cardboard and paper, Tour says. Using that hydrogen on a large scale to fuel cars, power plants, and other systems could reduce greenhouse gas emissions but would require fundamental changes to the entire energy infrastructure.

Tour says multiple companies have approached him to try to license the process. "Usually you wait years, and you try to beg somebody to take a look" at a new process or product, he says. "So this is off the charts." —*Rebecca Sohn*



Timema poppense, a species related to the stick insects studied in the new work

Moritz Muschick/University of Sheffield

GENETICS

Cryptic Sex

Female stick insects reproduce without males—but have a secret

CERTAIN WINGLESS, STICKLIKE insects that hide in bushes and trees across central California have no need for males: these insects in the *Timema* genus are nearly all female and reproduce without sex by creating genetic clones of themselves, a process called parthenogenesis.

But entomologists occasionally stumble on male *Timema* insects, which seem to have no reproductive function. "We initially assumed that the males were just errors, as loss of a single X chromosome can result in an egg developing into a male," says ecologist Susana Freitas, who led the study while working at the University of Lausanne in Switzerland.

Freitas and her team found that the uncommon males may engage in infrequent flings with the females. This "cryptic sex" introduces genetic diversity into stick insect populations and might aid their long-term survival. The team's genetic analysis was recently published in the *Proceedings of the Royal Society B.*

Parthenogenesis (meaning "virgin birth") is common among invertebrates and even occurs in some species of birds, lizards and snakes. For some, it's a last resort when mating options are limited; for others, it's their only method of reproduction. But creating offspring through cloning results in low genetic diversity, leaving a population vulnerable to harmful mutations and limiting its ability to adapt to environmental changes.

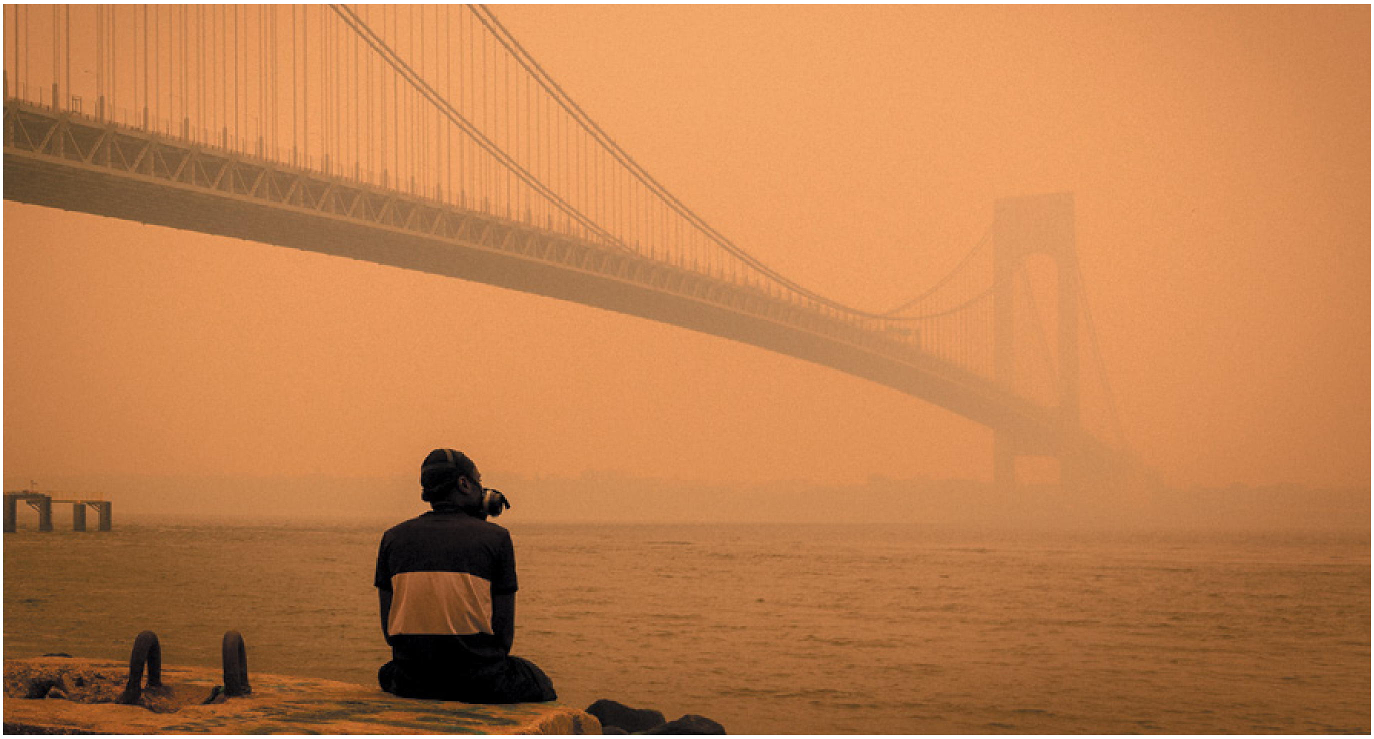
To examine the genetic diversity of the stick insects, researchers extracted DNA from females and rare males in eight *Timema* populations across four species. They then tracked the position of various genetic markers in each insect. These markers stay linked on chromosomes during asexual reproduction but are reshuffled with another individual's genes during sexual reproduction.

Most offspring genetically resembled their female parents. But offspring in two *Timema* species showed greater genetic diversity and fewer linked genes, indicating cryptic sexual relations. Tellingly, the genetic profiles of the uncommon males matched what would be expected from a rare sexual encounter.

The discovery "reinforces the hypothesis that many of the species previously thought to be anciently asexual in fact engage in sexual reproduction or other forms of genetic exchange," says Olga Vakhrusheva, an evolutionary biologist at the Skolkovo Institute of Science and Technology in Moscow, who was not involved in the new work.

These rare interactions, also known to occur among small crustaceans and water invertebrates, "could be helping to wash away any deleterious mutations," says Alexis L. Sperling, a crop scientist at the University of Cambridge, who also was not involved in the new study. She notes that many agricultural pests such as aphids, wasps and flies reproduce asexually. Cryptic sex or similar strategies could help these pests thrive, Sperling suggests—"but we need more research to be sure."

—Saugat Bolakhe



Peter K. Afriyie

ENVIRONMENTAL HEALTH

Out of Breath

Dirty air harms health in some surprising ways

AIR POLLUTION is one of the world's greatest public health threats, reducing global life expectancy more than smoking, alcohol or childhood malnutrition. Recent studies estimate that fine particulate matter called $PM_{2.5}$—pumped out by cars, factories, woodstoves and wildfires—causes nearly nine million premature deaths annually, with South Asia bearing the highest tolls.

$PM_{2.5}$ particles are tiny enough to enter the bloodstream and lodge in the lungs, where they contribute to respiratory problems such as asthma. They also can prompt heart attacks and strokes. And they have been linked to diabetes, obesity and dementia and may exacerbate COVID. As several recent studies demonstrate, the consequences of dirty air don't stop there. "We are finding out that particulate matter affects almost every aspect of our bodies and minds, from cognition to our heartbeats to our skin," says Christa Hasenkopf, an air-quality data expert at the University of Chicago. Though not involved in the three studies highlighted here, Hasenkopf expresses no surprise at the results, which "underscore literally thousands of other studies that show similar conclusions."

CANCER Living near high-traffic roadways or other areas rife with $PM_{2.5}$ increases the risk of breast cancer by about 8 percent, according to a study that examined 15,870 breast cancer patients in six U.S. states and two cities. Lead author Alexandra White, an epidemiologist at the National Institute of Environmental Health Sciences, speculates that airborne pollutants make people more susceptible to breast cancer by disrupting "the normal hormonal mechanisms in our bodies." White is also studying air pollution's impact on gynecological cancers, and other researchers have tied it to liver, pancreatic, prostate, lung and ovarian cancers, among others.

SMALLER BABIES Along with the elderly and already ill, babies tend to suffer the most from air pollution; it has been shown to impair their lungs, their immune responses and even their size. Women in northern Europe exposed to $PM_{2.5}$ and other air pollutants give birth to smaller babies, according to findings that Robin Mzati Sinsamala, an epidemiologist at Norway's University of Bergen, presented recently at a European Respiratory Society conference. Fine particles can penetrate the placenta and affect the "exchange of oxygen and nutrients between the baby and the mother," Sinsamala says, noting that infants with low birth weights face many health risks.

SUICIDE In the U.S., smoke from increasingly large and frequent wildfires impacts more than just physical health. David Molitor, an associate professor of finance at the University of Illinois at Urbana-Champaign, and his colleagues have found that the number of suicides ticks up in rural U.S. counties (though not urban ones) on smoky days. "It adds a little extra stress," Molitor says, "and sometimes that's all that's needed if you're in a vulnerable position to begin with." *—Jesse Greenspan*

If you or someone you know is struggling or having thoughts of suicide, help is available. Call or text the 988 Suicide & Crisis Lifeline at 988 or use the online Lifeline Chat.

Cold War Horse, a sculpture in Arvada, Colo., by Jeff Gipe, is a reminder of dangerous contamination from the Rocky Flats nuclear weapons plant, where Gipe's father worked for 20 years.

The New Nuclear Age

The U.S. is beginning an ambitious, controversial reinvention of its nuclear arsenal. The project comes with incalculable costs and unfathomable risks

PHOTOGRAPHY BY NINA BERMAN

For decades a Titan missile—sans top, which fell off—stood in a town park in Kimball, Neb. The missile was removed in September 2023 after it was deemed a safety hazard.

Boom Times

The new costs—and long shadow—of living in a nuclear nation BY ABE STREEP

PHOTOGRAPHY BY NINA BERMAN

THE POINT OF THE THING was to forever change our concept of power. When the U.S. military assembled a team of scientists, led by physicist J. Robert Oppenheimer, to build a nuclear bomb during World War II with the hope of beating the Nazis to such a terrible creation, many of those involved saw their efforts as a strange kind of civic destiny. The Manhattan Project, wrote Richard Rhodes, Pulitzer-winning author of *The Making of the Atomic Bomb,* was "compelled from the beginning not by malice or hatred but by hope for a better world." Oppenheimer himself once said, "The atomic bomb was the turn of the screw. It made the prospect of future war unendurable. It has led us up those last few steps to the mountain pass; and beyond there is a different country."

Abe Streep is a journalist and author of *Brothers on Three: A True Story of Family, Resistance, and Hope on a Reservation in Montana* (Celadon, 2021). He lives in New Mexico.

We live in that different country now, one in which it is assumed that the presence of nuclear weapons makes their use impossible. If one nation strikes, the thinking goes, we are all obliterated.

As recently as 15 years ago, the sentiment of nonproliferation seemed durable. Even American secretaries of state who held office during the cold war were advocating for the final drawdown of atomic weapons. Former president Barack Obama, when he took office in 2009, wanted a world without them and pushed a new treaty with Russia to limit the number of deployed warheads in each country's arsenal. But after decades of efforts to disarm global powers and reduce tensions, the screw is now tightening again. Russia has suspended its participation in the treaty, and it's believed that China is increasing the size of its arsenal.

And even while the U.S. was preparing to draw down its total number of nuclear warheads, it sought to replace its existing weapons and modernize its delivery mechanisms. The weapons, which had been designed decades ago, were aging, and their upkeep cost hundreds of millions of dollars a year. In 2010 Congress authorized an update to the U.S. nuclear triad, the weapons systems deployable by land, sea and air.

No leg of the triad is as controversial as the intercontinental ballistic missile (ICBM) system, the arsenal of hundreds of weapons spread across 450 underground silos in Montana, North Dakota, Wyoming, Colorado and Nebraska. Because the missiles sit in fixed locations—unlike submarines or aircraft—they are seen as potentially vulnerable to attack; because they are considered first-strike weapons, concerns linger that one could be inadvertently launched; because of their geographic sprawl, they have an outsize impact on land use and energy policy. In 2015, two years before General James Mattis was confirmed as U.S. secretary of defense, he suggested to the Senate Armed Services Committee that the military consider removing land-based missiles altogether.

But around the same time, the Air Force Nuclear Weapons Center requested the design and construction of a new missile. The contractor Northrop Grumman bid on it and won, and by 2021 Congress had authorized the first investments in an updated nationwide ICBM system, which is now called Sentinel. Like the Minuteman III missiles currently in the ground, the Sentinel missiles will be capable of making a graceful parabolic arc through the heavens to any place on Earth in order to destroy it. The $100 billion that will go to Sentinel represents only the first step of what is anticipated to be a $1.5-trillion investment in the triad, all of which is predicated on ramping up production of new plutonium pits, the deadly metallic hearts of nuclear warheads.

Whether the U.S. is turning the screw a little tighter to assure allies in the wake of Russia's newly aggressive stance and rising Chinese power or merely furthering

John Morrison, mayor of Kimball, Neb., at his High Point RV Park in August 2023. For years the town proudly called itself the missile capital of the world.

a profitable, decades-old militarized political agenda depends on whom you ask. Either way, the upshot is clear. "I expect the coming decades are going to be a boom time for the nuclear weapons industry," says Jeffrey Lewis, a nonproliferation expert and professor at the Middlebury Institute of International Studies at Monterey, Calif.

Robert Webster, deputy director of weapons at Los Alamos National Laboratory in New Mexico, told me that Americans have lost their fluency in nuclear weapons—that is, because of decades of relative stability, we've forgotten how to think about them. "You need everybody in the world to be on the same level of understanding so you can maintain this deterrence," he says. But global powers treat nuclear weapons as bargaining chips, and history shows that one country's escalation follows its rivals'. The worst-case scenario is apocalyptic. Even if an uneasy peace persists, we know from experience that a nuclear buildup—warhead production and the radioactive shadow it leaves behind—changes a place. "There's a cost of entry to being a nuclear country," Webster says.

It may be more accurate to say there are many costs to entry, both immediate and lasting. Since the advent of plutonium production, less than a century ago, some parts of the U.S. have borne more of those costs than others. This past summer I drove to the city that's still making the weapons it was supposed to eradicate the need for; to the plains where nuclear missiles control local economies; to a mine 2,000 feet underneath the desert floor where much of America's plutonium waste from weapons production goes to rest. My hope was to hear from people who live in those communities to better understand where that era has left them as we teeter on the edge of a new arms race. The tour started an hour away from my house, at the birthplace and spiritual home of America's nuclear weapons. "Los Alamos," says a sign at the edge of town, "where discoveries are made!"

LOS ALAMOS NATIONAL LAB, N.M.—The place looks staged, like a film set designed to represent a badly aging American suburb: the neat tan buildings, the security gates, the white domes resembling circus tents that house vessels full of plutonium waste. On a mesa backdropped by the Jemez Mountains, the place now known as Los Alamos National Laboratory (LANL) and the surrounding town were created during World War II, when the government acquired a boys' school and land from homesteaders and Indigenous people on the Pajarito Plateau. The plateau sits above steep canyons and arroyos that plummet to the valley floor and the Rio Grande, New Mexico's primary artery.

According to Raymond Martinez, director of the Department of Environmental and Cultural Preservation at the Pueblo de San Ildefonso, which borders the lab, the

Airmen at Camp Guernsey in Wyoming train for an attack scenario in which an enemy takes over a convoy vehicle transporting a nuclear missile.

tribe provided the government land for the war effort, with an understanding: "As far as our knowledge and our history that has been shared with us, and the information that we have found so far, once the project was done, the land was supposed to be returned," he said.

The Jemez are rounded, volcanic mountains, and they are full of life. There are elk and bear, kestrels and ravens, tall grasses and deer, and trout in deep, cool pools. It is a place where Indigenous peoples have come for millennia to hunt, fish, harvest wood and plants, and pray. In his 1976 memoir *The Names,* N. Scott Momaday, the Pulitzer-winning Kiowa author, recalled years he spent in the Jemez Pueblo as a boy: "Now as I look back on that long landscape of the Jemez Valley, it seems to me that I have seen much of the world."

What Oppenheimer saw on the mesa underneath the Jemez Mountains was a place where scientists could develop a weapon in secret. Early on, citizens of nearby pueblos helped to construct the town and worked as housekeepers for scientists. During World War II, LANL received uranium and plutonium from reactors at Oak Ridge, Tenn., and Hanford Engineer Works in Washington State, where the first full-scale nuclear reactor opened in 1944. The following summer bombers dropped two payloads on Japan: a uranium bomb, Little Boy, over Hiroshima and a plutonium device, Fat Man, over Nagasaki. That fall Oppenheimer resigned from LANL and was replaced by Norris Bradbury, who believed the lab needed to stay open to develop weapons as a deterrent. Even as Los Alamos widened its focus in the subsequent decades, becoming a home for climate science and nanotechnology research, it continued to create detonators for nuclear weapons.

At the height of the cold war the U.S. manufactured more than 1,000 plutonium pits a year, most of them at the Rocky Flats Plant in Colorado. The source uranium for those pits was scraped from the ground in mines in the Southwest, hundreds of them on Navajo Nation lands. In 1989 the Rocky Flats Plant was raided by the Federal Bureau of Investigation after numerous safety and reporting violations. The plant was shuttered; the surrounding land is now a wildlife refuge abutted by a sleek housing development.

After the closure of Rocky Flats, in 2003 LANL once again veered back into war-reserve pit production. It was soon tasked with making a limited number of pits for submarines, but that project was scuttled when it was revealed that scientists had put a number of pits side by side for the purpose of taking a photograph—a scenario that, hypothetically, could lead to a critical nuclear reaction.

Today there are an estimated 20,000 vintage pits in storage, many of them held in a plant in Texas called Pantex that disassembles, stores and reassembles old weapons. Whether those pits retain their efficacy is a matter of consequential debate. Plutonium produc-

A patch at F. E. Warren Air Force Base, one of three bases that oversees the U.S. intercontinental ballistic missile system.

tion from uranium began only 80 years ago, and testing of nuclear weapons in the U.S. has been discontinued since the 1990s. "We're kind of studying the aging as the experiment happens," Webster says.

Some studies have suggested that America's stockpiled pits will probably remain effective for a long time. "As far as we can tell, scientifically, there's no justification for needing to make new pits at the rate [the government] is proposing," says Dylan Spaulding, a senior scientist in the global security program at the Union of Concerned Scientists, who has done research at both LANL and Lawrence Livermore National Laboratory in California. Lewis of Middlebury's Institute of International Studies said the decision to update the arsenal is political and economic in nature: "We don't need the new ICBM."

But the National Nuclear Security Administration (NNSA) contends that this update is necessary to prevent decay and to maintain institutional expertise should a war effort become urgent. The U.S. Air Force maintains that updating the ICBM system is less expensive than paying to continue extending the life of the Minuteman III.

In 2018 LANL was told to get ready to produce 30 war-reserve-ready plutonium pits a year by 2026. (A new facility in South Carolina, under construction, will eventually contribute at least 50 plutonium pits a year.) Those will be made with recycled plutonium atoms sourced from Pantex's vintage stash of weapons and inserted into a warhead designed with new components. It marks the first time since the end of the cold war that the nation is manufacturing such a warhead, called the W87-1, which will be affixed to the end of the new Sentinel missiles.

To support the production of new plutonium pits, the annual budget for Los Alamos's nuclear weapons program and related construction has recently swelled to $3.5 billion—more than one-third the size of New Mexico's state budget. Webster says his team is hoping to produce its first war-reserve pit next year, but according to the Government Accountability Office, the project is behind schedule. The lab is planning to hire 1,400 workers, and the city is looking to find housing for them at a time when an influx of wealthy residents has reshaped the economic terrain of northern New Mexico. The county of Los Alamos, which has a median household income above $100,000, boasts that its residents "have the highest per-capita levels of educational attainment of any community anywhere."

Even as the new project begins, surrounding communities, many of which experience entrenched poverty, are still dealing with consequences from decades earlier. Back during the Manhattan Project, when there was scant environmental regulation, workers often dumped radioactive waste directly in the ground. At a former nuclear research center called Area C, for instance, there are still chemicals, including plutonium, uranium and tritium, in unlined shafts and pits from the Manhattan Project.

Elsewhere at Los Alamos the Department of Energy has committed to exhuming and removing the radioactive material and contaminated soils. But at Area C the DOE has proposed a cleanup strategy called "cap and cover" that keeps the waste in the ground. The state has objected. "We asked them to excavate the waste, sort it and dispose of it properly," says Neelam Dhawan, an environmental specialist with the New Mexico Environment Department's hazardous waste bureau.

Webster has maintained that the new production of pits will be safer than the last go-round, given what we now know about nuclear waste. Los Alamos is repeatedly inspected by the Defense Nuclear Facilities Safety Board, an oversight agency, which has found numerous protocol and safety breaches. A report from September 8, 2023, said technicians found radioactive material on a worker's protective bootie. Later that month electrical contract workers were exposed to hazardous beryllium dust while replacing lights. In 2020 a lab worker inhaled plutonium oxide powder—a terrifying prospect. This past May an NNSA investigation found that the lab's primary contractor in pit production, Triad National Security, had been negligent with safety protocols; the NNSA fined the contractor but still funnels billions of dollars in public money its way.

Webster disputes the idea that the lab has become less safe. Rather, he says, "we are seeing increased reporting of incidents," and he characterizes that as indicative of robust transparency. But for a state dealing with the long shadow of nuclear weapons, that's only so reassuring. "The nuclear industry has left New Mexico in a vulnerable position," says James Kenney, secretary of the New Mexico Environment Department. "Until we do right by those who are most impacted, we're not going to have the social license as a federal government or a state government to move forward."

F. E. WARREN AIR FORCE BASE, CHEYENNE, WYO., AND KIMBALL, NEB.—In western Nebraska, people like their nukes. In 1968 civic leaders in Kimball, the so-called missile center of the world, sought one from the U.S. Air Force to display in its town park. They received a Titan, a precursor to the Minuteman. A local newspaper rhapsodized: "The community erected a huge missile in one of its parks to show people it wasn't kidding."

At the time Kimball was booming thanks to investments in nearby missile silos at F. E. Warren Air Force Base, located just outside Cheyenne, Wyo. But since 1970 Kimball County has shrunk from 6,000 people to about 3,300. John Morrison, Kimball's mayor, who owns a gas station and an RV park in town, told me he is hoping for a surge of people and business from the Sentinel project: Warren is the first of three air force bases that will receive the Sentinel missiles, and Northrop Grumman is designing an elaborate new command center here. It'll be the nerve center of an ICBM system connected by a webbed system of transmission lines.

The 53-year-old Minuteman missiles remain operational. But some years from now, the first Sentinel missile will arrive at Warren and will likely be loaded onto a containment vessel. This so-called transporter erector will back up to a flat place in a field, probably in the vicinity of a farm. Fencing surrounds the place; underneath the ground, there is a silo. The airmen operating the erector will use hydraulics to tilt it toward the skies, and the brand-new missile will slip into the ground, where it will await the arrival of its warhead.

Given the location of the silos, it's possible to think of the missiles as deadly seeds spread across the prairie. But the people who operate them see them differently. "We call it a parent and a child," says Major Cory Seaton, a 33-year-old missileer at Warren. The child is the launch facility, including the silo and the missile itself; the parents are the missileers sitting about eight stories underground at a distant missile alert facility, inside a capsule containing three switches and a key that, when turned simultaneously, launch a nuclear strike.

The missileers I met at Warren were young. There was Second Lieutenant Gavin Jones, 23 years old with a baby face; he'd joined to get college paid for and because he liked structure in his life. Too many of his friends lacked direction, he said. He worked with First Lieutenant Joshua Wuthrich, 28 years old, who "wanted to do something with meaning," he said. Wuthrich had become interested in the work when he learned about Hiroshima as a child. "It stopped the war in two days," he said. "The more I learned, the more I liked it."

Much of the missileers' work involves security checks and maintenance; there's a constant need for them in these 60-year-old facilities. The equipment inside the cramped capsules is old, too—there are square monitors, the type of knobs you see in Sean Connery James Bond films, and a rotary phone. The air force base just transitioned data from years' worth of nuclear missile maintenance and checks off floppy disks.

Outside, past a heavy steel door, is an equipment room with two rumbling diesel generators, one of which featured an intake vent covered in duct tape. Graffiti art covered the walls outside the capsule: images of missileers golfing, nature scenes, a memorial to Kobe Bryant. Past a blast-proof door, a freight elevator led back to the surface of the earth. On the elevator shaft, someone had drawn murals reminiscent of the postapocalyptic video game *Fallout*. One read, "Be aware of the nuclear wasteland!"

Earlier this year it was revealed that more than 100 missileers in Montana have developed cancer, including rare forms such as non-Hodgkin's lymphoma. In response to the revelations, the air force ordered a cleanup of missile alert facilities in Montana that have been shown to contain polychlorinated biphenyls, or PCBs—toxic chemicals believed to have accumulated on equipment inside the poorly ventilated capsules. According to an air force spokesperson, 17 samples taken at Warren tested positive for PCB, but all were below acceptable levels. The air force is still testing for PCBs and other potential hazards there.

The air force is not digging any new silos, but it does plan to redesign the old ones. The current silos descend as deep as 90 feet underground and have concrete casings—features designed to help the nukes withstand a potential enemy attack. But the new silos will be closer to the surface and will have less armor. (Northrop Grumman, which has a $13.3-billion government contract to design the Sentinel missile and

Biochemist Michael Ketterer takes soil samples in Truchas, N.M., to look for plutonium residue from the Trinity test, Los Alamos weapons production and the Nevada nuclear tests.

related infrastructure, did not release further details.) When the first silos were dug, their precise locations were a secret. That's no longer the case; Russia and China know where they are.

As an added layer of security, the military is using a new, high-performance helicopter, the Boeing Grey Wolf, to be able to swiftly respond to any threats to missile silos. The Grey Wolf is said to be 50 percent faster than its predecessor. But it has been locally controversial.

Warren's silos alone cover nearly 10,000 square miles in Wyoming, Nebraska and northern Colorado. For years wind-energy companies had been looking to develop projects near missile silo farms in Nebraska. Air force regulations held that any turbines need to be located at least 1,200 feet from silos, and the companies had drawn up plans accordingly. But the air force recently extended this setback to 2.3 miles out of concern that rotating turbines might interfere with the new helicopters. That change has greatly reduced the size of what would have been Nebraska's largest wind-energy project. "They say this is a necessary thing to protect our country," says Jim Young, a longtime farmer and landowner in western Nebraska, who supports the wind project because it would reduce property taxes. "Depends if you believe that or not."

Northrop Grumman is planning to build a live-in camp for around 2,500 workers who will revamp the transmission infrastructure needed to rewire and reconnect Warren's 150 silos. The incoming workers, however, aren't expected to be permanent. Mayor Morrison is aware of the reputation of such workers—temporary "man camps" have been associated with increased crime—and says Kimball has already bumped up funding for law enforcement.

But Morrison expresses no hesitation about the project. Maybe it will even result in a new missile in the town park. The old Titan stood for decades until someone from the air force showed up in the early 1990s to remove its upper half, out of concern that it might be emitting radiation. A new tip was affixed but poorly, and a wind event later brought it crashing to the ground. Pigeons roosted inside the exposed shaft. "Quite a bit of pigeon poop had gotten into there," Morrison says. The community took the Titan down this past September. Morrison initially wanted to replace it with both a Minuteman and a Sentinel, but he had been told that might entail too much radiation.

RIO GRANDE VALLEY, N.M.—New Mexico has incredible green chile, world-class elk hunting and sporadic bursts of open political graft. It's also known for its spectacular billboards. Casinos promote maturing rockers, and Albuquerque features a veritable ecosystem of personal-injury attorney ads. In the 1990s people traveling through the state were treated to a sign funded by an activist group that read:

A remembrance event was held for cancer victims in Las Cruces, N.M., in July 2023, organized by the Tularosa Basin Downwinders Consortium. New Mexicans exposed to fallout from the 1945 Trinity test have never been eligible for government support.

"WELCOME TO NEW MEXICO, AMERICA'S NUCLEAR WEAPONS COLONY." Drive around the communities near Los Alamos these days, though, and you'll see the lab's own messaging campaign. This summer one billboard showed a smiling young woman in a lab coat with gloves. "Radiation Control Technicians Are Vital to Operations at LANL," it read, next to a promotion for a job-training program at Northern New Mexico College.

I passed by it in June while driving to Moving Arts Española on Ohkay Owingeh Pueblo. Inside, about 20 people had gathered to discuss how the government would clean up radioactive and chemical waste at Los Alamos. Under a wall display of masks, cooks served tostadas with fresh salsa. Michael Mikolanis, who manages the field office at Los Alamos for the DOE's Office of Environmental Management, stood out for his jacket and tie and a conspicuously big turquoise bracelet.

Mikolanis studied nuclear engineering in college and served on a nuclear submarine in the U.S. Navy before eventually pivoting to a career of cleaning up nuclear waste. Two years ago he was sent to New Mexico, where he is tasked with improving a complicated relationship between Oppenheimer's city on the hill and neighboring communities. As journalist Alicia Inez Guzmán, who grew up nearby, put it in a recent article for *Searchlight New Mexico,* "There's a kind of mental acrobatics required to compartmentalize these different realities—the opportunity and the harm, the secrets and the consent."

For nearly two decades Los Alamos used hexavalent chromium to prevent scaling in water-cooling towers at a power plant that supplied the lab. The chemical is toxic and is thought to cause cancer when ingested. Often the lab just flushed the hexavalent chromium down canyons toward the Rio Grande, and in 2004 scientists reported that it had leached deep into the ground. It is now in the aquifer's groundwater, and although a monitoring well on the Pueblo de San Ildefonso hasn't shown evidence of contamination, the plume is awfully close. "We don't have a very good understanding of where it dripped into the aquifer," Dhawan says.

To mitigate the underground plume, the DOE spent $120 million on monitoring and treatment systems; extraction wells that remove contaminated water; and injection wells that send treated water back into the ground. But the New Mexico Environment Department has expressed concern that the injections of clean water could move the plume toward San Ildefonso. The DOE has temporarily paused some of the injections. There are plans to drill another monitoring well. Meanwhile the plume creeps.

Then there's the radioactive material from the Manhattan Project and the cold war—what the DOE calls "legacy waste," which is found at old weapons-development sites. It rains a lot in New Mexico during the summer—enough to cause flash flooding and to reshape arroyos; a 1999 study by scientists from Los Alamos found evidence of unnatural plutonium and

Most of Mary Martinez White's family members have had cancer; some have died from it. She has long advocated for Congress to extend benefits to New Mexicans affected by the Trinity test.

uranium levels in the bed of Cochiti Lake, downstream, on the Pueblo de Cochiti. To prevent storm runoff from carrying plutonium and other radioactive waste to the Rio Grande, the government constructed weirs to redirect rainstorms into catchment and monitoring zones at human-made wetlands in 2000.

Over dinner, Mikolanis spoke rapid-fire about taking out a "loan of trust" and wanting to improve transparency. He acknowledged that the government has earned skepticism from local communities, but he still needed to project assurance. He noted to me that the plutonium found in Cochiti Lake was "1,000 times below levels that would generally trigger cleanup for radiological concerns" and suggested that the uranium found there might have come from a nearby mine. Regarding the risk of extreme weather, he said, "a number of controls and measures are put in place" to keep contaminants secure. Fully harnessing a monsoon, though, is like extinguishing a megafire, another attendant threat to Los Alamos: it's not possible.

Los Alamos has long downplayed concerns about undiscovered contamination, trying to assure local communities that all the legacy waste from the Manhattan Project era has been identified. In 2020, however, construction workers digging a sewer came across a previously unidentified disposal area that was revealed to contain plutonium and uranium. What's important, Mikolanis emphasized, is that he promptly and frankly communicated about it to neighboring communities and nations. "That transparency, that accountability, should still earn their trust," he said, "because things will happen."

After dinner, Mikolanis and his colleagues spoke for nearly an hour, giving an overview of the cleanup projects at hand. The room was dark, so attendees had trouble making out both the slides and a handout covered in acronyms. Then we were asked to move to breakout tables, where, for 10 minutes at a time, staffers asked pointed questions about the priorities of the constituents. It was basically speed-dating but for nuclear-waste mitigation.

I sat with Kathy Wan Povi Sanchez, an Elder from San Ildefonso Pueblo and a co-founding mother of Tewa Women United. She wore her silver hair swept back and a KN95 mask hanging from a beaded necklace. Her first match was Mike Narkter, a communications official for a subcontractor that works for another contractor that receives $230 million a year for the legacy waste cleanup. Narkter asked what her priority was.

"I guess being a dual citizen," Sanchez said, "I think it's not so much prioritizing." She gave him a history lesson—about the neglect of those who made the bomb, about the disrespect to cultural sites, about the waste creeping toward land her people had tended since time immemorial. "Nothing that is put in the ground stays immobile," she said. She noted the pub-

Luminaria remembrance event for cancer victims was organized by the Tularosa Basin Downwinders Consortium in July 2023.

licly funded vocational program at Northern New Mexico College to train workers to handle radioactive waste—the subject of the new billboard advertisements. "To me that's not valuing the cultural aspect of a person to choose what will be a sustainable way of being tied to the land base that they come from."

Among the most heavily guarded facilities at Los Alamos is a region called Area G, which is close to San Ildefonso tribal lands. Here lab workers manage and dispose of plutonium lingering from decades ago. Liquid waste produced during the processing of plutonium has been entombed in cement that is encased in corrugated metal piping. In one of the white domes, a massive conveyer belt runs the piping toward a device that slices it into manageably sized pieces. It looks like the world's biggest cigar cutter. Sanchez said the removal of these plugs wasn't enough. "Just because they dug it up, sent out that cement canister thing, doesn't mean the land around there has been remediated." She asked Narkter if she was making sense, and he allowed that it was "a lot to unpack." A buzzer sounded. Time was up.

Narkter moved to another table, and a woman named Sarah Chandler came to replace him. Chandler wanted to know what Sanchez was most concerned about. Sanchez explained that there were a few things. "We're wandering in trauma while the lab is still trying to clean up," she said, adding that the lab had not helped itself by "being so sloppy and messy the way they did the business and from the beginning being so arrogant." She suggested that the lab conduct more outreach to other tribal nations. A buzzer sounded. Someone else arrived and asked Sanchez what values should guide the cleanup. They asked again and again until Sanchez said what she really wanted Los Alamos's nuclear weapons program to do: "Get out of there. Get your dirty-work business out of there."

To the north of Area G, a steep, rocky chute called Mortandad Canyon reaches down the Pajarito Plateau like a crooked finger toward the Rio Grande Valley, carrying runoff to the river. When Sanchez and her husband, J. Gilbert Sanchez, a former San Ildefonso governor, were growing up in the 1950s, they and their friends and family fished in the river. He told me he would run down with hot tortillas and fry up silver minnows to eat. Then one day he was warned not to eat fish from the river. He hasn't fished there since. "From my understanding of the history, LANL was created with the understanding it would revert back to us after the war ended," Gilbert Sanchez said when I talked to him months later. "The war has never ended, I guess."

THE PERMIAN BASIN, SOUTHERN NEW MEXICO— If the communities surrounding Los Alamos have a fraught relationship with America's nuclear weapons industry, matters are less politically complex where Los Alamos's plutonium goes to rest. The final repository for much of the U.S.'s transuranic nuclear waste is a mine, the Waste Isolation Pilot Plant, or WIPP, located in the southern part of New Mexico, between Carlsbad and the oil town of Hobbs. "WIPP is the community," says Carlsbad city councilman JJ Chavez, who also happens to work at WIPP as an environmental support supervisor, "and the community is WIPP."

The company-town inclination dates back decades. Before the advent of hydraulic fracturing caused the latest oil boom here—horizontal drilling has turned the Permian Basin, which stretches from New Mexico into Texas, into the nation's largest oil reserve—this

A missile park is located on the U.S. Army White Sands Missile Range in New Mexico, near where the Trinity test was conducted in 1945.

region was a potash-mining community. That business was temperamental, and town leaders saw nuclear-waste storage as a job-creation vehicle. So in the 1970s they advocated for an underground repository. Congress authorized exploration, which started in 1981, with miners drilling toward a 2,000-foot-thick bed of rock salt left behind by the Permian Sea. It is ever shifting, so tunnels bored inside the salt will eventually collapse on themselves, encasing anything within. "I believe that's the greatest resource we have in this county," says Farok Sharif, a former president of Nuclear Waste Partnership, the contractor that managed WIPP until last year. "Pristine salt."

It wasn't until 1992 that Congress passed a bill, the Land Withdrawal Act, that gave WIPP space to operate. Seven years later the mine started storing transuranic waste from weapons production. The waste arrives inside cylindrical steel containers holding 55-gallon drums full of contaminated gloves, rags and protective booties, as well as the cement plugs that encase what was once liquid plutonium. The vessels are driven on tractor trailers from Los Alamos or other sites in the nationwide nuclear complex, past the scars of old uranium mines and down toward the southern desert, where Oppenheimer and his colleagues tested the world's first nuclear bomb in 1945.

WIPP sits amid oak and cactus in a great flat; air shafts rise out of the ground, funneling oxygen into the mine below. At a warehouse the drums are removed from the steel containers and loaded onto a forklift, then sent down an old freight elevator. The elevator descends to a network of mine-shaft access areas known as panels. Each panel contains seven rooms; they are lined with bolted metal fencing to keep small pieces of salt from fall-

ing in too quickly. Here the waste goes to sit and await the glinting salt. Eventually the fencing will fall inward.

Down in the salt, miners wear powerful headlamps and helmets while driving around in open vehicles and stand on lifts while bolting in new fencing. In the elevator shaft, people talk about bass fishing. Up on the surface, WIPP is a busy place on account of a massive, $500-million construction project to build two new structures—one that filters salt out of the air coming from a shaft below and one equipped with an advanced filtration system that can treat any unintended radiological releases from underground.

During a tour of the construction in August, communications officials made oblique references to "the events" that had necessitated this new ventilation system: a vehicle fire and then a radiological release, both in 2014. The latter event was caused by a compromised drum that had been improperly sealed at Los Alamos. In advance of my visit, one of the communications officials was careful to emphasize that, despite the large new buildings I'd see, WIPP is not expanding. The official line is that the facility is updating its infrastructure and moving toward filling up its congressionally mandated space.

But opponents of nuclear weapons modernization point out that WIPP and Los Alamos are inextricably linked because the production of new warheads requires a repository for waste products. For much of the past year WIPP was negotiating with the state over a renewal permit allowing it to construct two more long-planned panels. On the tour, Ken Harrawood, president of SIMCO, the contractor managing WIPP, pointed me toward a map of the facility and said, "We are not expanding the scope, but we are in fact expanding the footprint."

"No, we are not expanding the footprint," said our guide, a DOE spokesperson.

"Yeah, we are," Harrawood replied. "We are adding panels in the mine to receive the same amount of waste that's always been approved."

The absurdity of this moment cut to the quick of America's nuclear project. The weapons complex is spread through multiple bureaucracies; each one is responsible only for its own discrete tasks and relies on language that can be gymnastic. The officials who manufacture warheads often use less aggressive phrases such as "modernization program" to refer to new investments in the triad; those responsible for cleanup suggest reliability, even in the face of incontrovertible "events"; those overseeing the missiles call them "children."

In 1987 feminist scholar Carol Cohn published a classic academic essay, "Sex and Death in the Rational World of Defense Intellectuals," examining the curious rhetoric of the nuclear weapons complex. Cohn interrogated the obvious phallic imagery of the missile—"If disarmament is emasculation, how could any real man even consider it?"—but also the more subtle linguistic obfuscations that, she theorized, frame the existence of nuclear weapons as at once beneficial, inevitable and controllable. This animating political logic drives the project's forward momentum. "The old cold war never really ended institutionally," says Zia Mian, co-director of Princeton University's Program on Science and Global Security. "The core structures remain exactly the same."

In October, New Mexico approved WIPP's permit for the new panels, with conditions: the facility must prioritize legacy waste over new plutonium, and should Congress dictate an expansion of the mine's intake, the state will immediately begin the process of closing WIPP down. But Kenney, the New Mexico Environment Department secretary, ultimately wants WIPP to remain open. "Is it safe for the pueblos around LANL and the city of Santa Fe to have that waste remain at Los Alamos?" he asks. "I don't think so."

"This is a really, really important project for the nation," Harrawood says. That project requires workers, and recruitment is a challenge given the easy availability of high-paying oil jobs. The DOE has invested nearly $12 million in job-training curricula for radiological workers at nearby Southeast New Mexico College. According to David Porter, an Idaho contractor and nuclear industry veteran who designed some of the programs, students can pay $5,000 and emerge from a four-month radiological control technician course with a strong likelihood of a job at WIPP or Los Alamos. To maximize the efficiency of the training, Porter has stripped out ancillary lessons. "We don't do English, sociology or psychology. It's all just the industry," he says. "Folks graduate on Friday, and they go to work Monday." It is a vertically integrated nuclear employment system, allowing applicants to choose whether they wish to handle America's plutonium at its cradle or at its grave.

TULAROSA AND TRINITY TEST SITE, SOUTHERN NEW MEXICO—Spend 40 minutes at the Bradbury Science Museum in Los Alamos, and you can watch a plutonium bomb detonate on repeat. Inside the museum, which commemorates the atomic age, footage loops of the Trinity test, the 1945 explosion in southern New Mexico that marked the world's first nuclear detonation and preceded the bombings of Hiroshima and Nagasaki. In a darkened theater, the detonation of the so-called gadget is blinding. The light fills the room; the light takes away everything.

The Bradbury Museum refers to the Trinity test site as remote. If you spend time in rural parts of the country, this is a characterization you encounter often: places lacking human density are remote, a word that implies vacancy. But remoteness depends on your center.

Tularosa, or Tulie, as it's locally known, is a town of about 2,500 people on the desert floor at the foot of the Sacramento Mountains, about a four-hour drive south from Los Alamos. The region was settled in the 1860s by Spanish settlers who warred with the area's original stewards, the Mescalero Apache, who still live nearby. The settlers developed ranches here, attended mass at an old mission church, and served in the U.S. military. In 1945, when Oppenheimer's gadget blew up about 60 miles to the northwest, Tularosa residents reported being knocked to the ground.

Soon scientists at Lawrence Livermore National Laboratory will begin using El Capitan: a supercomputer billed as the strongest in the world, which will "facilitate regular use of high-resolution 3-D simulations of W87-1 warhead in operation." In other words, El Capitan will perform nuclear weapon tests virtually so they do not need to be done in the physical world. "You would never go back to aboveground testing," Webster of Los Alamos says. "We had to stop that. There was too much fallout."

Mary Martinez White grew up in Tularosa in the 1950s and 1960s. Her father worked at Holloman Air Force Base near Alamogordo, ordering supplies for daily operations. At the time of the Trinity test, he and White's mother were living in Carrizozo, a railroad town that is even closer to the explosion site. He was proud of his work, and he died of leukemia. When White was 10, her brother's friend, who was 27, died of leukemia. White's mother and sister died of cancer; three other siblings have survived cancer.

"Downwinders," as they are called, in Nevada, Utah and Arizona who suffered negative health impacts from cold war–era nuclear weapons tests performed at the Nevada Test Site have long been eligible for financial support. But such benefits have never been extended to New Mexicans affected by the Trinity test.

White has long advocated for Congress to do so. "New Mexico was predominantly people of color," White says. "Mescaleros, Mexican Americans. We didn't have running water. We were a dispensable, disposable population." Still, she describes her family as patriotic. She lost a nephew who served in the U.S. Army Special Forces in the Iraq War. "It's unnerving to think the government is not acknowledging you when they're looking to you for so much," she says.

Earlier this year, in the wake of Christopher Nolan's movie *Oppenheimer,* the U.S. Senate passed a measure that could offer New Mexicans who developed cancers after being exposed to radiation from the Trinity test $150,000 and medical bill coverage. The bill would also extend support to Navajo uranium miners who have been excluded from downwinder benefits. The measure is tied up in a larger defense-spending package, but White seems cautiously optimistic. "We are closer than we have ever been before, but we know how much we still have to lose," she says. White is especially frustrated by the investment of federal dollars in job-training programs to recruit young people from communities like hers. "The first weapons were tested on us," she says, "and now our kids are funneled into it."

Has she ever visited the Trinity test site?

"No," she says. She has no desire to go. She's been there all her life.

North of Tularosa, the highway intersects another road at Carrizozo. Left past the sharp black volcanic formations, the land starts to roll. There is sotol and sage and wispy grasses. Near Bingham a turnoff heads back to the south, past signs advertising Trinitite—the eerie green glasslike rock that the Trinity test created when the reaction melted the sand. I turned down that dirt road and drove to a rise from which I could see the sculpted ridge of the Oscura Mountains to the southeast and the San Andres Mountains to the southwest. Down the valley, way in the distance, a blue peak gathered a raincloud. In the center of everything was a sprawling flat where, 78 years ago, an explosion turned the sky white.

If you didn't know what you were looking at, you might think of it as empty—a canvas, a place to reshape in one's own image. That's what certain Americans have done for generations in these wide-open spaces, out of malice or naivete or hope. We rush forward; we cannot imagine the past collecting its due. Heat shimmered on the still land. Then the wind picked up. ⬢

With reporting by Nina Berman.

Inside the Pit Factory

For the first time in decades the U.S. is ramping up production of plutonium cores for nuclear weapons

BY SARAH SCOLES

A mockup of a plutonium pit is shown at Los Alamos National Laboratory in the 1940s, where Manhattan Project scientists were developing the first nuclear weapons.

WITHIN EVERY AMERICAN nuclear weapon sits a bowling-ball-size sphere of the strangest element on the planet. This sphere, called a plutonium pit, is the bomb's central core. It's surrounded by conventional explosives. When those explosives blow, the plutonium is compressed, and its atoms begin to split, releasing radiation and heating the material around it. The reaction ignites the sequence of events that makes nuclear weapons nuclear.

In early nuclear bombs, like the ones the U.S. dropped on Japan in World War II, the fission of plutonium or uranium and the fatal energy released were the end of the story. In modern weapons, plutonium fission ignites a second, more powerful stage in which hydrogen atoms undergo nuclear fusion, releasing even more energy. The U.S. hasn't made these pits in a significant way since the late 1980s.

But that is changing. The country is modernizing its nuclear arsenal, making upgrades to old weapons and building new ones. The effort includes updated missiles, a new weapon design, alterations to existing designs and new pits. To accomplish the last item, the National Nuclear Security Administration has enacted a controversial plan to produce 50 new pits a year at the Savannah River Site in South Carolina and 30 pits a year at Los Alamos National Laboratory in New Mexico, the birthplace of the bomb. The first pits will be designed for a weapon called W87-1, which will tip the new intercontinental ballistic missile, called Sentinel. After that the complex will produce pits for other bomb designs.

Not everyone believes this work is necessary. Pit production foments controversy because it's costly and potentially risky and because the existing pits might still work for a while. The physics of plutonium is complex, and no one knows when the original pits will expire. The details of how the pits are made and how they work are among America's most closely guarded secrets. Yet in June 2023 Los Alamos officials invited a group of journalists to tour the facility for the first time in years.

We were there as the lab and the broader National Nuclear Security Administration Complex were embarking on a charm offensive to support the new plutonium work. They have to win over the tax-paying public and recruit some 2,500 new employees for the job. Some of those workers must do high-hazard work that requires expertise the country has largely let slip since the last days of the cold war. Back then, many thought the world was heading toward disarmament, and the skills necessary for a nuclear resurgence seemed unlikely to be called for. That's not quite what happened. Instead China is rapidly growing its nuclear arsenal, and Russia, at war with Ukraine, touts new missile tests and its own nuclear modernization. The U.S. is doing the same. The world order feels fragile; the renewed focus on nuclear weapons threatens to create a 21st-century arms race and an increased reliance on the shaky peace that nuclear weapons may or may not help keep.

Sarah Scoles is a Colorado-based science journalist, a contributing editor at *Popular Science* and a senior contributor at *Undark*. She is author of *Making Contact* (2017) and *They Are Already Here* (2020), both published by Pegasus Books. Her book *Countdown: The Blinding Future of Nuclear Weapons* (Public Affairs) will be out in 2024.

MUCH OF THE PLUTONIUM work at Los Alamos takes place in a building called PF-4, which is located south of town in a part of the lab complex called Tech Area 55. It is one of the most highly guarded parts of the lab. Before our tour, we're told to survey our hands, forearms and ankles for scrapes or scratches into which radioactive contamination could slip. Onto these abrasions we're instructed to place technical protection: Band-Aids. The message is repeated within the building by a sign that instructs those entering to "occlude your wound."

A jarring mix of upbeat friendliness and deadly seriousness greets us at the facility. A cheerful wood sign outside the building welcomes visitors, and security guards fistbump as we walk in. But those same guards wear long guns, and their eyes swivel tightly as we pass through a TSA-like portal into the bowels of the building. A security force will follow the group—who have been parted from phones, cameras and recorders, as well as all metal, nylon and polyester—the entire afternoon.

Once we're past the initial screening, we step into an airlock with yellow doors on either side of a capsular room. Only one door can be open at a time to keep potential radiological contaminants trapped within PF-4. After we pass through without setting off the alarm, we put on anticontamination lab coats—color-coded red for visitors without security clearance and yellow for the people who belong here. We scrunch disposable booties over our shoes (the se-

Los Alamos National Laboratory (*preceding page*)

At Los Alamos's Plutonium Facility, in a building called PF-4, the U.S. plans to produce new plutonium pits for a renewed nuclear weapons program.

Los Alamos National Laboratory

curity guards get camo shoe covers). Safety goggles slip over our faces, and radiation badges are clipped to our fronts, measuring the invisible energy and particles that whip through them. All plutonium work has been paused for the day to conceal the classified details of pit production.

Element 94, as plutonium is also known, is rare. Dying stars produce a small amount during their last, hot gasps, but that star stuff had decayted nearly out of existence before Earth formed. The planet has made a bit of its own: in what is now Gabon, Africa, algae concentrated natural uranium over the eons, forming a natural fission reactor that produced four tons of plutonium. That plutonium, too, has since decayed away. Scientists inferred the existence of the natural nuclear reactions from the ratio of uranium isotopes that were left in modern times.

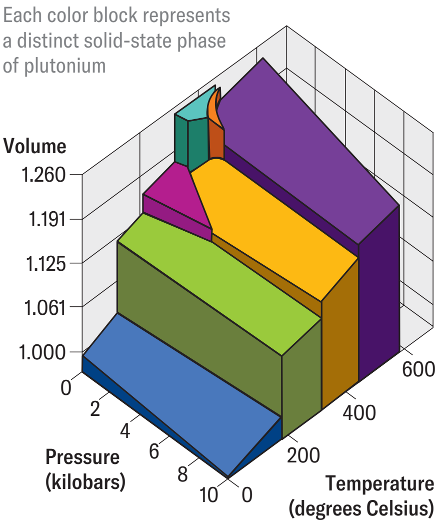
The plutonium used for weapons exists only because people made it. In 1940 scientists used a particle accelerator at the University of California, Berkeley, to bombard an isotope of uranium (which has 92 protons per atom) with nuclei of deuterium (a proton and a neutron stuck together). That created neptunium (93 protons per atom), which conveniently decayed into plutonium with its 94 protons per atom. Thus, one of the most efficient ingredients for making a nuclear weapon was born. It's easier and cheaper to make enough plutonium for a weapon than it is to produce enough enriched uranium, the only other element used to sustain a fission chain reaction in nuclear weapons. And fission is what achieves the pressures and temperatures necessary to ignite fusion in the secondary part of the bomb.

Plutonium's genesis was repeated in reactors for decades. In fact, scientists made so much that no new plutonium is required for the new pits at Savannah River and Los Alamos—the current supply can be repurposed, reshaped, reborn.

None of those actions, though, will be simple because plutonium is not simple. Joseph Martz, a scientist in Los Alamos's materials science and technology division, has spent his career mapping the specifics of that complication. Martz started working with plutonium while he was still in college, manipulating it within protective glove boxes that shield workers from radiation. He's never forgotten the first time he touched element 94. Even through thick gloves and from behind glass, he could still feel it: the kilogram of material in his hand was warm. "I remember actually being a bit afraid," he says. "I had almost a terror reaction."

Since then, his fear has given way to fascination with the substance. There is plenty to be fascinated by. It's pliable and compliant in some conditions and delicately brittle in others. When it's a liquid, melting around 650 degrees Celsius, it's the most viscous of all the elements, dripping languidly. If you heat it in its solid form, sometimes it expands, and other times it contracts. It's reactive with air, swiftly shifting its appearance from a silvery metal to a rainbow spectrum of tarnish. When it solidifies, it expands, like water, and its length and density change without much provocation. Its most famous trick, of course, is its propensity for radioactive decay, through which it transforms itself out of existence.

Plutonium can take six different solid states at ambient pressure and seven solid states at higher pressures.



This tendency is also what makes it so dangerous. Inhaled plutonium decays in the body, releasing alpha particles (helium nuclei) that can wreak havoc. The isotope plutonium 238, used as a heat and power source but not in weapons, exhibits other strange behaviors. “If you spill it in the laboratory, it will move around on its own,” Martz says. The oomph from a plutonium atom’s decay sends it shooting across a surface. “It can get everywhere,” he adds.

Plutonium’s strangeness comes from its arrangement of electrons. The element occupies the part of the periodic table where atoms’ “5f subshell” begins to fill. That’s relevant to plutonium’s behavior because the “f” electrons reside in narrow energy bands that overlap, allowing the electrons to slip between the bands easily. When they do, Martz says, “the nature of those ‘f’ electrons changes behavior dramatically.” Change the temperature, for instance, and some of the electrons bond with nearby atoms “in very complex shapes,” Martz says. The combinatorics mean that plutonium comes in six different solid phases, each with its own crystal structure and strange behavior.

It’s taken scientists decades to discover all of this. “What we know today to be the complexity of plutonium was not known to the Manhattan Project scientists,” Martz says. For years those secret scientists didn’t actually have any plutonium to study—it had to be painstakingly produced. “Almost everything was theoretical,” says Alan Carr, senior historian at Los Alamos. “In lieu of the actual material, they’d have chalk and chalkboards and notebooks.” The first full gram of element 94 arrived on Los Alamos’s mesas in April 1944. The substance had already perplexed the researchers. When they took basic measurements of characteristics such as density, they saw huge variations. Eventually they were able to make their first hemispheres of plutonium metal—protoversions of the pits of today, the size of a golf ball. Yet when they came to the lab the next day ready to experiment, they found that the hemispheres had cracked because their properties and dimensions had shifted. “It was maddening,” Martz says.

A breakthrough came later in 1944, when one Manhattan Project scientist suggested that combining plutonium with another element to make an alloy might stabilize it in a phase that was workable. The problem was, they didn’t know which element might work. According to a historical document Martz discovered, the scientists had a very scientific method for deciding what substances to try: “Whatever we found in the cupboard,” they wrote. Eventually they discovered that gallium did the trick. It’s still used in pits today.

IN THE EXCITEMENT of these early scientific discoveries, the point of the work would sometimes get lost: it was all in the service of creating a deadly superweapon. In 1945 the U.S. dropped a uranium fission bomb on Hiroshima and then sent a plutonium bomb—essentially a pit encased in explosives—to devastate Nagasaki. The bombs killed tens of thousands of people immediately and more after the fact. As Manhattan Project physicist I. I. Rabi had feared, according to a quotation in the 2005 book *American Prometheus,* “the culmination of three centuries of physics” was a weapon of mass destruction.

Soon after the war, production of plutonium pits migrated to a facility outside Boulder, Colo. Called Rocky Flats, it could churn out thousands of pits a year—a level of productivity perhaps enabled by its violation of environmental regulations, which in 1989 resulted in a federal raid and then a permanent shutdown. “The public wasn’t considered at the time,” says Bob Webster, deputy director of weapons at Los Alamos. Not long after, as a result of a testing moratorium and treaty, the country’s nuclear weapons complex underwent another phase shift. Scientists and engineers had always tested weapons in the easiest way possible: by blowing them up. If they exploded as expected, officials froze the design and made more clones of that weapon. The researchers never had a true understanding of why everything worked or what might cause it not to—or of how both those things might change over time.

But in 1992 President George H. W. Bush announced a moratorium on nuclear testing. Sig Hecker, at the time director of Los Alamos and now a professor at Stanford University, was in Washington, D.C., when he heard the announcement. “I came back to Los Alamos and told our people, ‘Look, the world has just changed,’ ” he says. They were going to have to maintain the stockpile by understanding its physics without testing it. That task has proved particularly complicated for the plutonium pits, which are all now decades old. Because plutonium was first synthesized only 80 years ago, no one’s been able to observe how it behaves as its life wears on past that point.

How aging affects a pit is the subject of contention, but some things are certain: As the plutonium atoms in a pit decay, their products damage the crystal structure of the plutonium that remains, creating voids and defects. These decays also contaminate the pit with helium, americium, uranium and neptunium, among other things. In 50 years a kilogram of plutonium will amass around 0.2 liter of helium. As pits change, their performance and safety in any conditions—including just sitting on a shelf—become questionable. Pavel Podvig, a senior researcher at the United Nations Institute for Disarmament Research and a researcher with the Program on Science and Global Security at Princeton University, who has questioned the motivation for modernization, concedes, “If you maintain the arsenal, at some point it would be safer to have new pits.”

Scientists still don’t know the lifetime of a plutonium pit. JASON—a clandestine group of scientists that provides advice for the government—first projected in 2007 that the pits would last decades longer, implying no production program was necessary. But it changed its stance in 2019, stating, “We urge that pit manufacturing be re-established as expeditiously as possible in parallel with the focused program to understand [plutonium] aging.” The National Nuclear Security Administration’s own studies have suggested the pits will last at least 150 years but also that their degradation could result in surprise defects. And scientists may never know exactly what those defects do or how they would affect

Modified version of a chart from “New Pressure-Temperature Phase Diagram of Plutonium,” by J. R. Morgan, in *Plutonium 1970 and Other Actinides: Proc. 4th Int. Conf. on Plutonium and Other Actinides.* Edited by W. N. Miner. Metallurgical Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers, 1970. Adapted with permission from The Minerals, Metals & Materials Society an explosion because the ostensible point of nuclear weapons is to never use them.

SO FAR RESTARTING American pit production is proving challenging. Los Alamos's efforts are at least a year behind schedule, and Savannah River's are more like five years delayed.

The Defense Nuclear Facilities Safety Board and other critics have claimed that PF-4 isn't resilient enough against the kind of earthquake geologists now know could occur in Los Alamos. Such significant shaking and the fires it could cause, the board alleged at a hearing last year, could result in plutonium contamination that reaches the public. Inside PF-4 our tour group encounters a poster laying out the lab's Seismic Analysis of Facilities and Evaluation of Risk, also known as SAFER, a program that has resulted in upgrades to the building itself and the equipment within. In 2022 the safety board deemed this modernization to be still not quite good enough.

Some at the lab disagree, including Matt Johnson, head of pit production, who's leading us through PF-4. "If there is an earthquake, this is where I want to be," he says, gazing at the poster. Other safety concerns have come up recently, though. In May the National Nuclear Security Administration released an investigation about four 2021 incidents: one criticality safety violation, one breach that resulted in skin contamination for three workers, and two flooding events that sent water toward fissionable materials. The agency determined that the contractor that manages Los Alamos had violated safety, procedural, management and quality-assurance rules.

Webster, also on the tour in his official yellow lab coat, says the lab and its workers take safety seriously but admits problems are inevitable. "We will always have issues at the lowest level," he says. If everything started going perfectly, he says, they would lower the limit of what counts as a safety violation so people would still get practice reporting. But, he notes, the cutoff is already low: "Rooms would get shut down if they were as radioactive as Fiestaware."

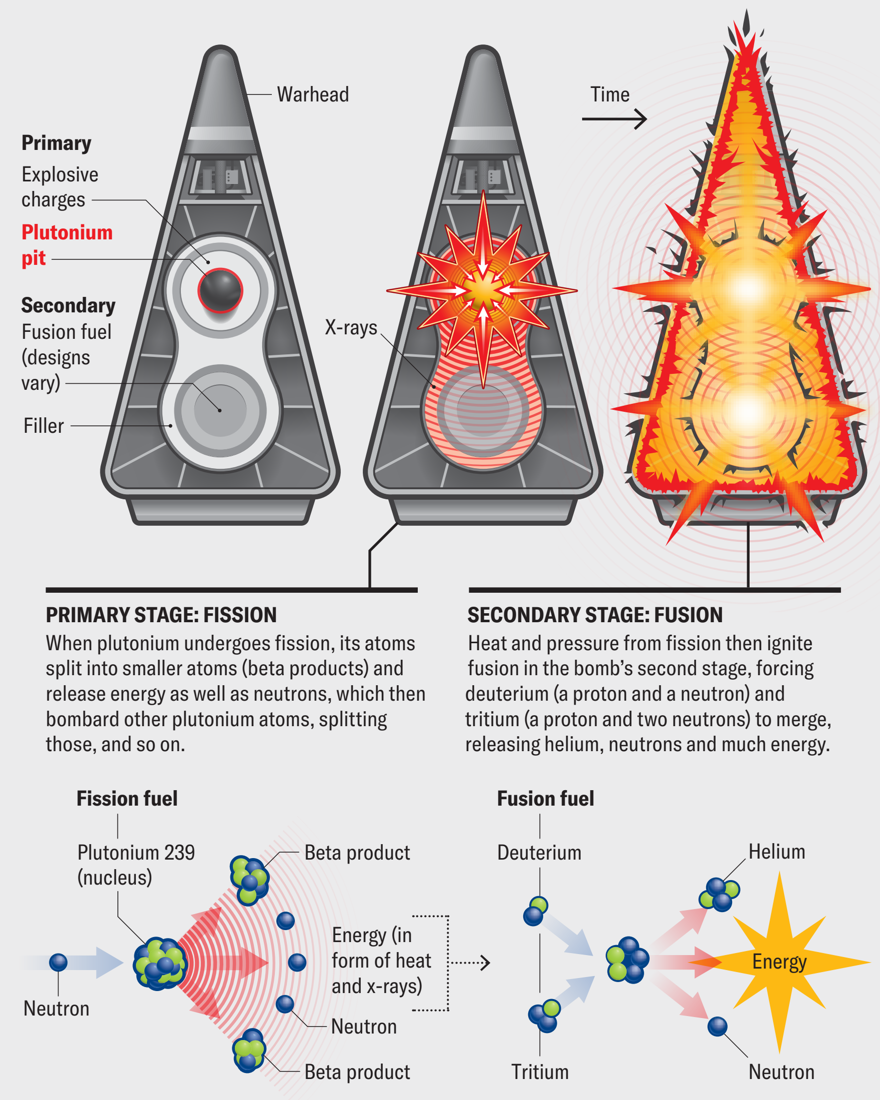
Those rooms, dedicated to various parts of the pit-production enterprise, all have one thing in common: they're full of glove boxes, the radiation-protective equipment inside which workers manipulate plutonium. Long gloves are sealed to openings in glass so sheathed hands can touch samples safely. The gloves themselves have dates written on them so workers know when to replace them. Everyone wears two pairs. The glass windows are surrounded by a metal box that looks like it could be made of plutonium: dull silver with smooth, rounded corners, which are easier to clean and harder for particles to lodge in. "You could eat off this," Webster says. "Not in here," he adds.

On the tour, we are forbidden from setting our notebooks down lest potential contamination stick to them. Should we drop them, a radiological control technician—who has been following us the whole time and scans our hands and feet for radioactivity anytime we leave a room—would measure each page before returning them.

In some places the glove box windows are covered by aluminum foil, blocking classified material from our view. Above these boxes, in every room, there is a kind of trolley system that workers use to move plutonium from room to room. In some rooms, radioactive waste is packaged and waiting to go to a storage facility, with the dosage one might receive from standing near it

How Plutonium Pits Work in Nuclear Weapons

Plutonium pits form the core of modern nuclear bombs. They are made of plutonium 239, one of the only elements in the world that can sustain a fission chain reaction. When explosives around the pit go off, the plutonium gets compressed and fission is ignited. The plutonium blast in turn sets off an even more powerful second-stage explosion fueled by nuclear fusion.



Graphic by Nick Bockelman

written on the ground. We are never allowed to forget that this is a dangerous place.

The workers who make pits face these risks every day. To do their jobs, they must first recover and purify plutonium from the old material. Then they "cast," or shape, the plutonium into pieces. Once cast, the pieces must be fitted together into a whole. Standing near the place where that happens is the first woman to ever assemble pits, whose name we cannot publish for security reasons. She assembled her first pit in 2013 (between 2007 and 2013 the lab produced 31 pits). Today putting a pit together takes her 30 minutes to an hour. "Everything is by touch, by feel," she says. She likes the work, some of which happens in a glove box that's two stories tall. "It's peaceful in the glove box," she says.

Once she or another worker has finished a pit, it gets micromeasured and constitutionally scrutinized to confirm it meets specifications. If it gets a stamp of approval (with a literal stamp, shaped like a diamond), it will go to the Pantex facility in Texas to be placed in a nuclear warhead. In the years to come, if all goes as planned, that process will happen at least 30 times a year here.

ALL OF THIS EFFORT and investment is being made in the hopes that the pits never serve their active purpose. The U.S., like all nuclear nations, stockpiles weapons in a delicate game of deterrence, the idea being that the existence of our equally or more capable weapons will stop others from using theirs. In this strategy, the pits' true purpose is to sit idly as a threat. But for the strategy to work, the country must be willing to follow through on that threat.

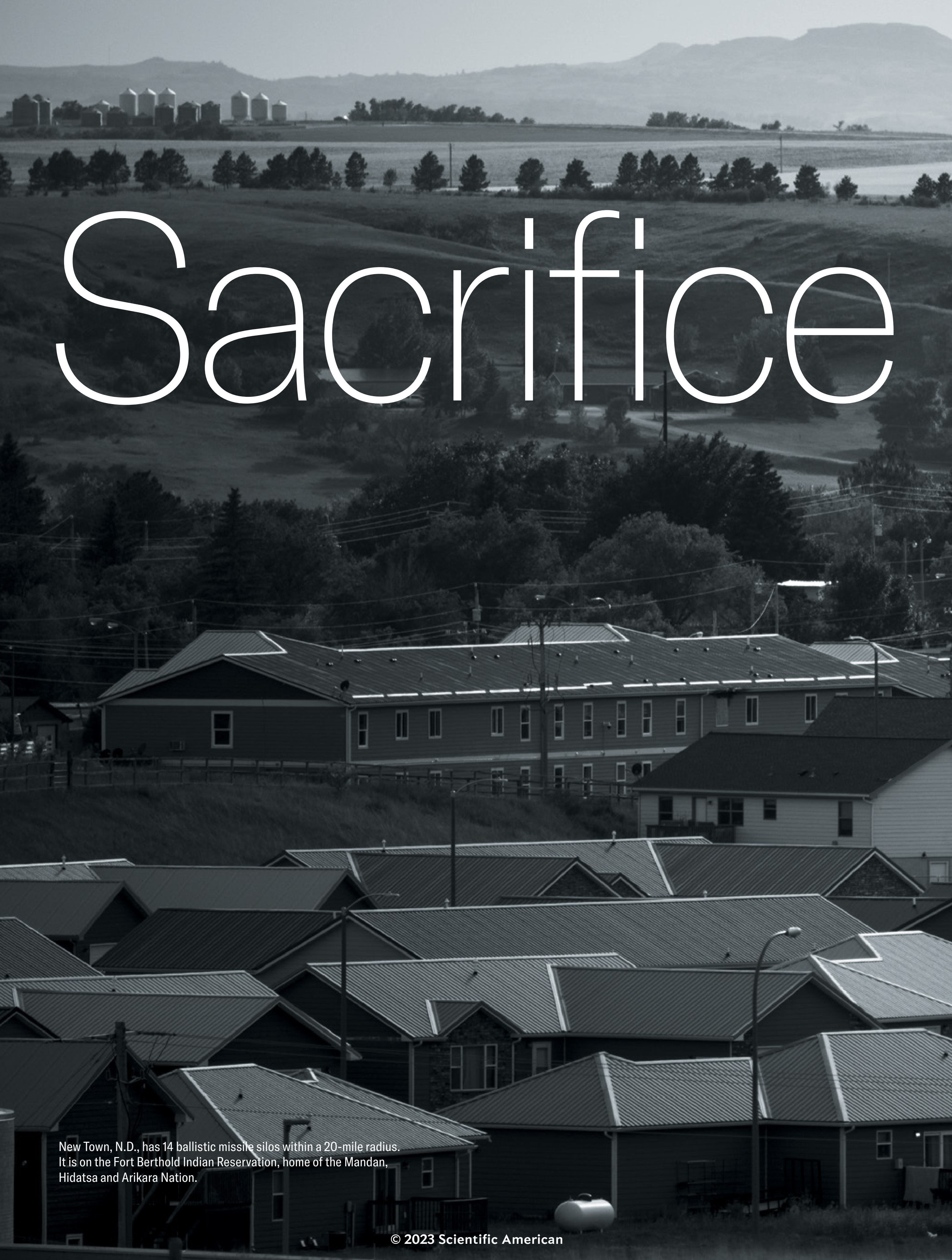
As we leave PF-4, permanently installed instruments once again scan our hands and feet for radiation. After that, in an airlock, a full-body scanner sniffs for alpha, beta and gamma radiation on our bodies. Even though contamination is unlikely, we sigh with relief when the all-clear comes.

We go back to our lives, where we can easily forget about plutonium pits. After the cold war many Americans got used to these weapons. "At some point it became so normal it was forgettable," says Idaho State University nuclear historian Sarah Robey. The fear people feel when confronted with plutonium has degraded over time. But the atomic age is renewing, and we will all have to grapple afresh with the coiled terror of these powerful weapons. ●

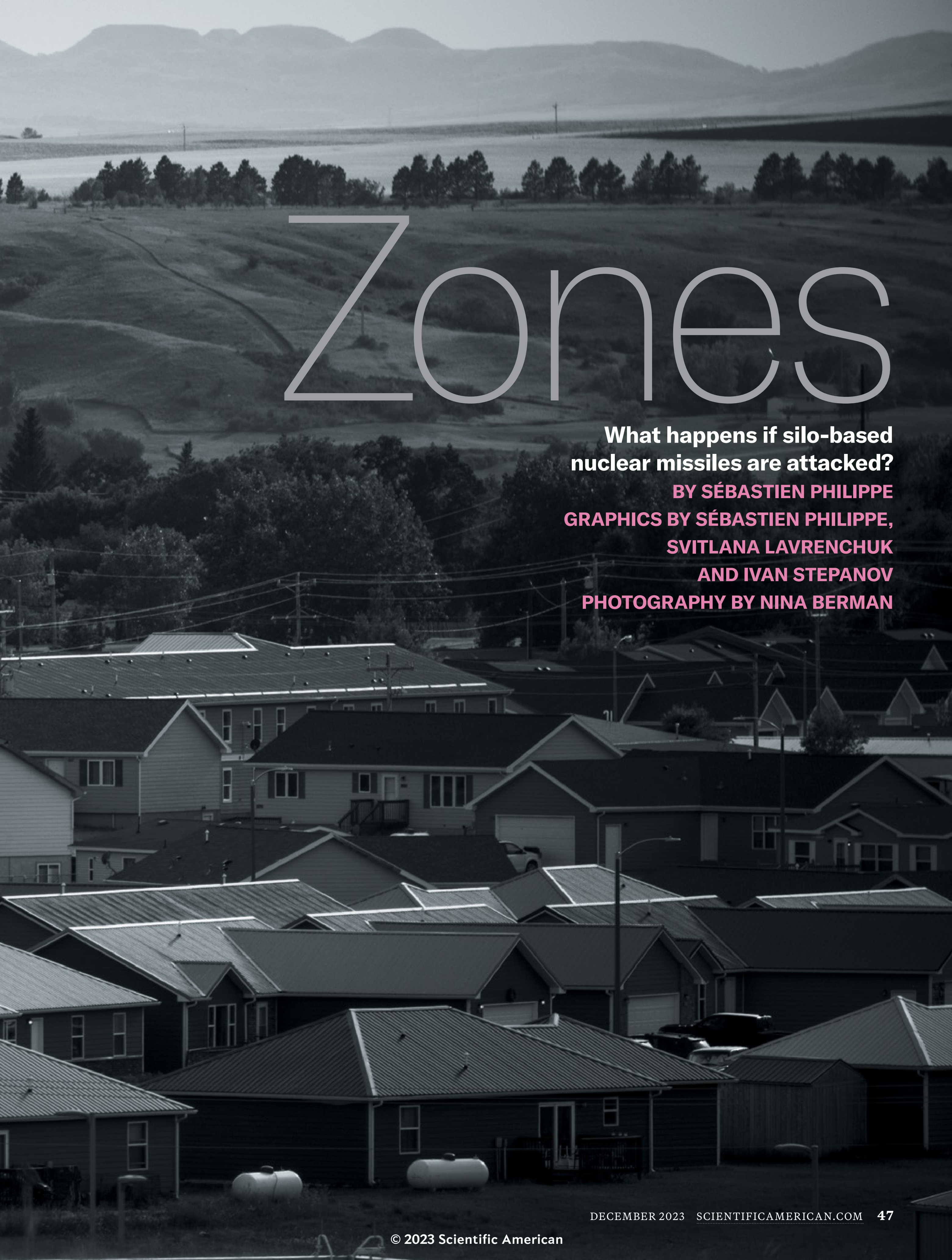
Photograph by Nina Berman

Three intercontinental ballistic missiles—the Peacekeeper, the Minuteman III and the Minuteman I—are displayed at F. E. Warren Air Force Base in Wyoming.

Sacrifice



New Town, N.D., has 14 ballistic missile silos within a 20-mile radius. It is on the Fort Berthold Indian Reservation, home of the Mandan, Hidatsa and Arikara Nation.



Zones

What happens if silo-based nuclear missiles are attacked?

BY SÉBASTIEN PHILIPPE

GRAPHICS BY SÉBASTIEN PHILIPPE, SVITLANA LAVRENCHUK AND IVAN STEPANOV

PHOTOGRAPHY BY NINA BERMAN

LAST MARCH THE U.S. AIR FORCE released a two-volume, 3,000-plus-page report detailing the environmental impact of its plans to replace all 400 "Minuteman" land-based intercontinental ballistic missiles (ICBMs) with new "Sentinel" missiles by the mid-2030s. The program is part of a $1.5-trillion effort to modernize the U.S. nuclear arsenal and its command-and-control infrastructure. The report, required by the National Environmental Policy Act of 1970, covers the "potential effects on the human and natural environments from deployment of the Sentinel system" and from, among other things, the refurbishing of existing missile silos and the construction of new utility corridors and communications towers. But it doesn't mention the most significant risks to surrounding communities—namely, what happens if these missiles, which are intended to serve as targets for enemy nuclear weapons, are ever attacked.

The original purpose of the land-based missile system was to deter an enemy nuclear attack by threatening prompt and devastating retaliation, but a key argument for the continued existence—and now the replenishment—of the land-based missiles is to provide a large number of fixed targets meant to exhaust the enemy's resources. Since 1962, when the first ICBMs were installed in the U.S. heartland, competition from other legs of the nuclear triad has forced the rationale for land-based weapons to evolve. By the 1970s, when the U.S. Navy deployed long-range submarine-launched ballistic missiles, the air force had placed 1,000 Minutemen in silos across seven states. As missile-guidance systems improved, it soon became clear that the land-based weapons were vulnerable to attack because of their fixed locations, whereas the stealthy sea-based weapons were much better protected.

The air force used the vulnerability of the land-based missiles to argue for their necessity. In 1978 General Lew Allen, Jr., then air force chief of staff, proposed that the silos offered "a great sponge" of targets in the U.S. to "absorb" incoming Soviet nuclear weapons. Destroying the missile fields would require such a massive attack that adversaries couldn't manage it or even contemplate it. Absent the land-based missiles, the argument goes, an adversary would have far more resources available to seek out and attack other U.S. military and infrastructure targets or even cities.

Even if an adversary is rational enough to not initiate a full-scale attack, the land-based missiles greatly increase the risk of accidental nuclear war. To preclude the possibility of enemy weapons destroying the missiles in their silos, the air force maintains the fleet on high alert, ready to launch on an order from the president—within minutes of enemy missile launches being detected. This "launch on warning" posture makes land-based missiles the most destabilizing leg of the U.S. nuclear triad (which also comprises the missiles based on aerial bombers and submarines). During the cold war there were several false alarms about enemy attacks. If a similar error precipitates the launching of the ICBMs, the adversary will almost certainly retaliate by launching its own nuclear arsenal at military, industrial and demographic targets in the U.S.

Attacking a missile silo requires detonating one or two nuclear warheads, with explosive yields equivalent to 100,000 tons of TNT, close to the buried target. The resulting nuclear explosions will generate gargantuan fireballs that will vaporize everything in their surroundings and produce destructive shock waves capable of wrecking the missiles in their launch tubes. Because the warheads will detonate close to the ground, the nuclear fireballs will suck in soil and other debris and mix it with radioactive bomb effluents as they rise in the air. About 10 minutes after detonation, the mixture of debris and fission products will form miles-high radioactive mushroom clouds, which will then be dispersed by high-altitude winds, leading to fallout on downwind areas.

Studies of the projected fallout from a nuclear attack on the missile fields, published in *Scientific American* in 1976 and 1988, showed that radioactive particles could travel hundreds of miles downwind. A 1990 guide from the Federal Emergency Management Agency on risks and hazards from natural and nuclear calamities

Sébastien Philippe is a scientist at Princeton University's Program on Science and Global Security. He develops methods for monitoring nuclear weapons and models the impact of nuclear explosions.

A nuclear missile is buried under the white concrete silo door to the left in this picture. The entrance to the silo, which lies just west of Garrison, N.D., is monitored constantly by cameras and other sensors.

confirmed these assessments, adding that no locality in the U.S. was free of the risk of receiving deadly levels of radiation. Today FEMA's publications about the effects of nuclear explosions focus on single nuclear detonations; the agency no longer publishes countrywide assessments of risks from nuclear attacks.

All these past studies relied on relatively simple fallout models and average seasonal winds. Current computational capability, along with higher resolutions in archived weather data, allows scientists to map the radiological risk from a preemptive nuclear attack on the missile silos in unprecedented detail. The results of my simulations, presented here for the first time, paint a harrowing picture of the potential consequences of living with these weapons for the foreseeable future.

According to my models, a concerted nuclear attack on the existing U.S. silo fields—in Colorado, Wyoming, Nebraska, Montana and North Dakota—would annihilate all life in the surrounding regions and contaminate fertile agricultural land for years. Minnesota, Iowa and Kansas would also probably face high levels of radioactive fallout. Acute radiation exposure alone would cause several million fatalities across the U.S.—if people get advance warning and can shelter in place for at least four days. Without appropriate shelter, that number could be twice as high. Because of great variability in wind directions, the entire population of the contiguous U.S. and the most populated areas of Canada, as well as the northern states of Mexico, would be at risk of lethal fallout—more than 300 million people in total. The inhabitants of the U.S. Midwest and of Alberta, Saskatchewan, Manitoba and Ontario in Canada could receive outdoor whole-body doses of radiation several times higher than the minimum known to result in certain death.

Even if there is no nuclear war, people in communities near the missile fields will continue to face serious risks that are also not discussed in the environmental impact statement. One is the accidental release of radioactive materials, such as plutonium, in the warheads by a mechanical shock, fire or explosion. A second is the accidental detonation of a warhead leading to a nuclear explosion. The history of the U.S. nuclear missile program provides several examples of silos or missiles catching fire and of missiles exploding in their launch tubes. One time, in 1964, a warhead fell from the top of its missile to the bottom of its 80-foot-deep silo. Nuclear weapon accidents are not always discussed publicly. The air force hasn't disclosed, for example, the nature of a 2014 "mishap" that occurred while personnel were troubleshooting a Minuteman. The episode caused $1.8 million in damages to the missile, which had to be removed from its silo.

The air force needs to be far more transparent about the true risks of its land-based nuclear missile fleet so the U.S. public can make informed decisions about living with this danger for another half a century. ⬢

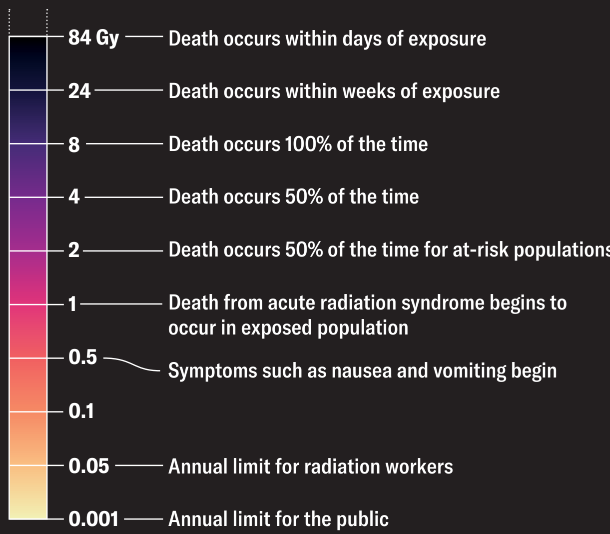
FROM OUR ARCHIVES

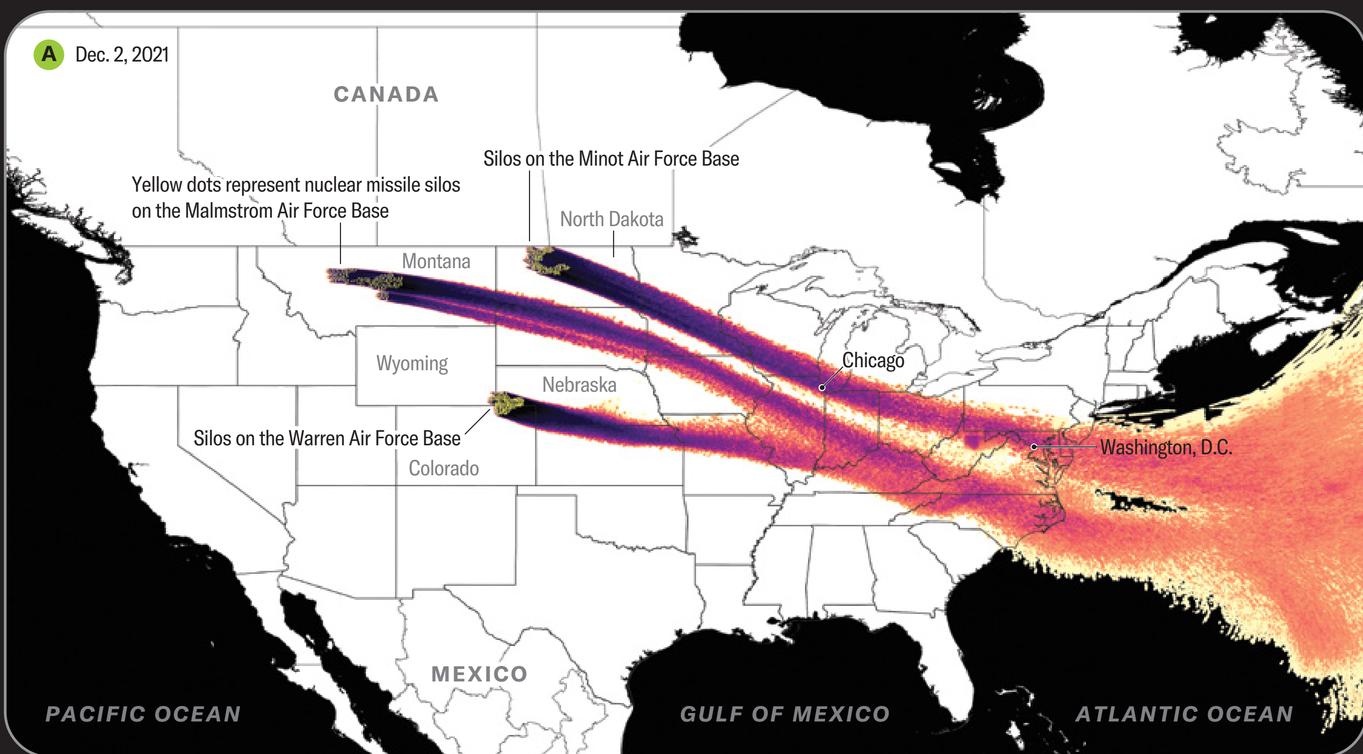
Broken Shield. Laura Grego and David Wright; June 2019.
ScientificAmerican.com/magazine/sa

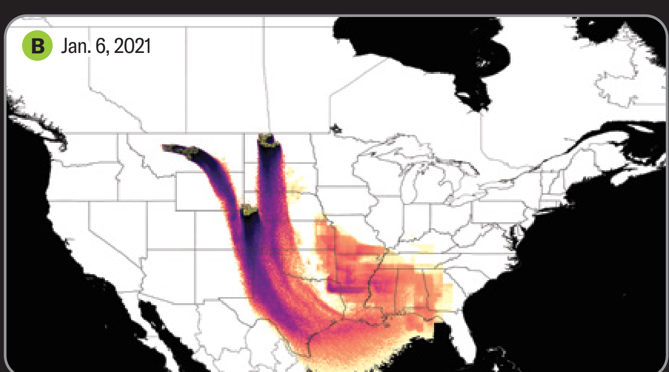
How Fallout and Fatalities Shift with the Winds

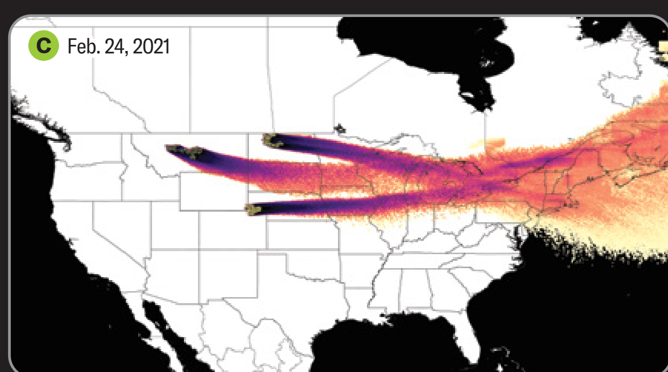
A concerted nuclear attack on the missile silos in the U.S. heartland would generate radioactive dust that travels with prevailing winds. Sébastien Philippe and his colleagues at Princeton University's Program on Science and Global Security used archived weather data to simulate the paths of the resulting plumes for 48 hours, by when most of the dust settles. Because wind directions change daily, the researchers computed fallout dispersal from an 800-kiloton warhead detonating simultaneously at each of 450 silos on any given day of 2021. The selections (*below*) demonstrate the variability of wind directions and, consequently, of the doses of outdoor radiation received over four days of exposure to radioactivity. The scientists further combined these simulations with data on population density and building height to calculate the resulting fatalities (*far right*). Someone absorbing four grays (equivalent to four joules of radiation energy per kilogram of body weight) would have a 50 percent chance of dying (*right*), but people sheltering in bigger buildings would receive smaller doses. Depending on wind directions, a nuclear attack on the missile silos could kill several million people.

Cumulative Radiation Dose after 4 Days, in Grays
One gray (Gy) is equal to an absorbed dose of one joule per kilogram

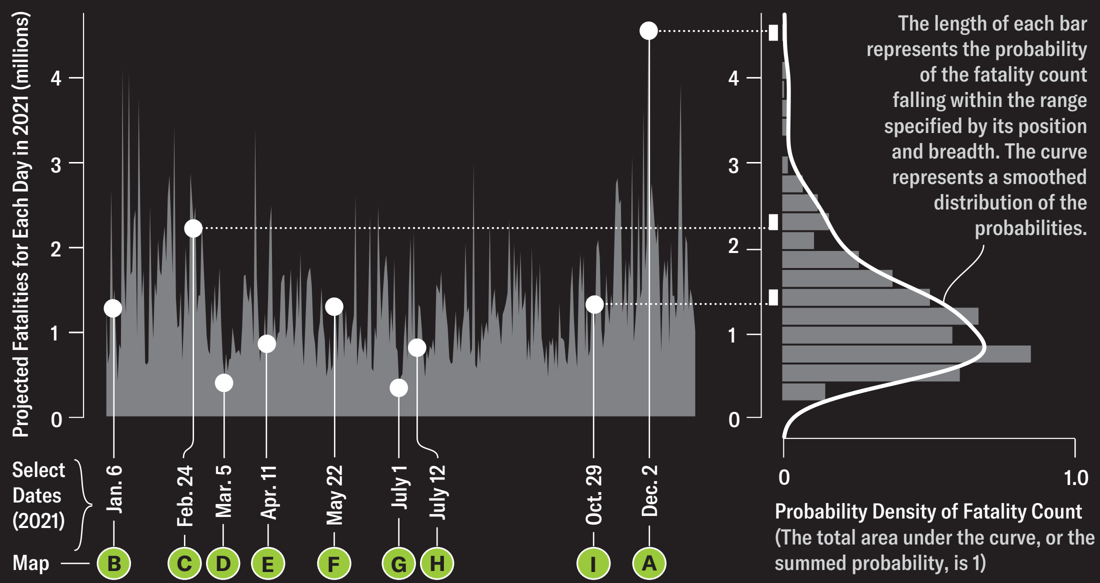


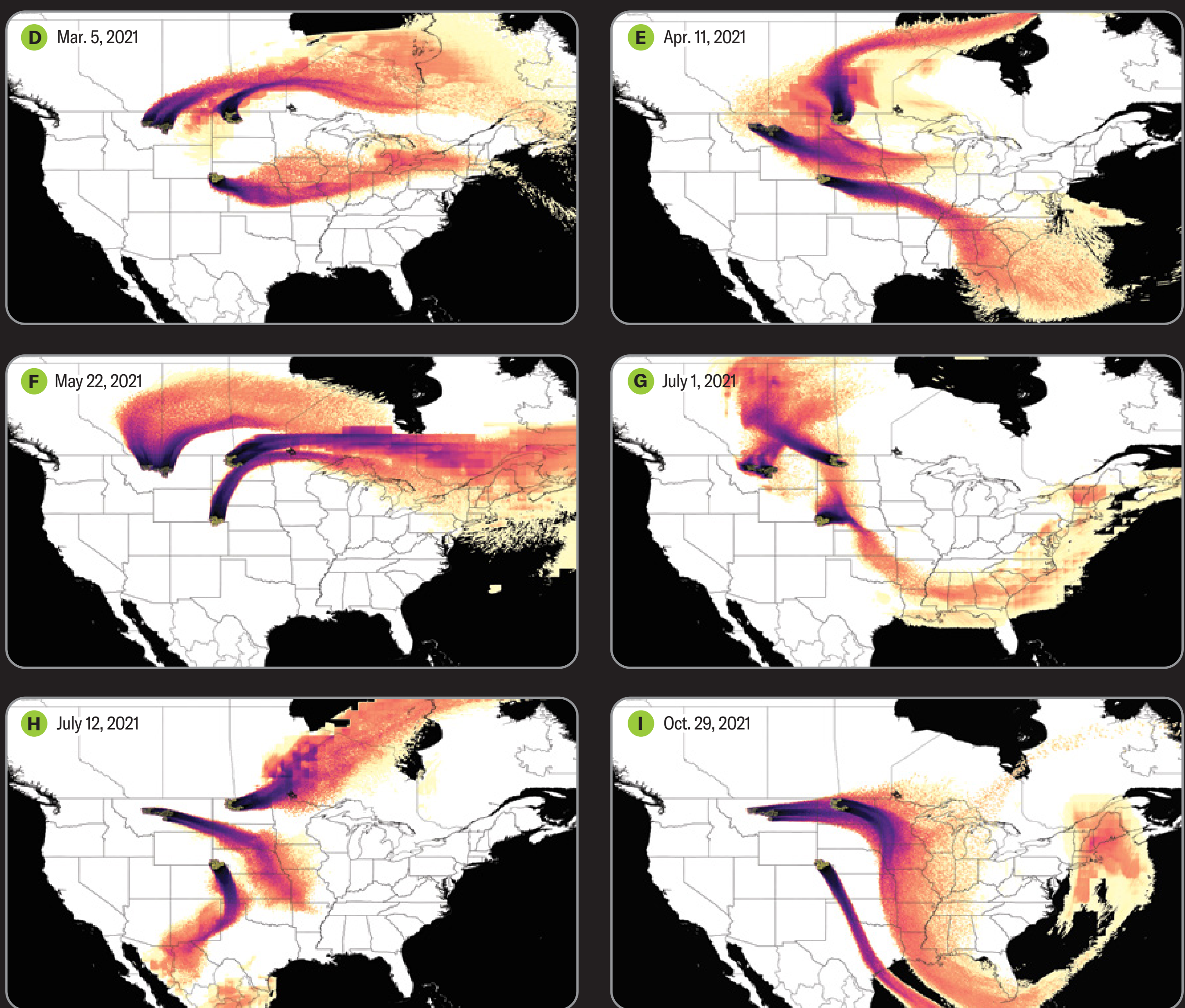


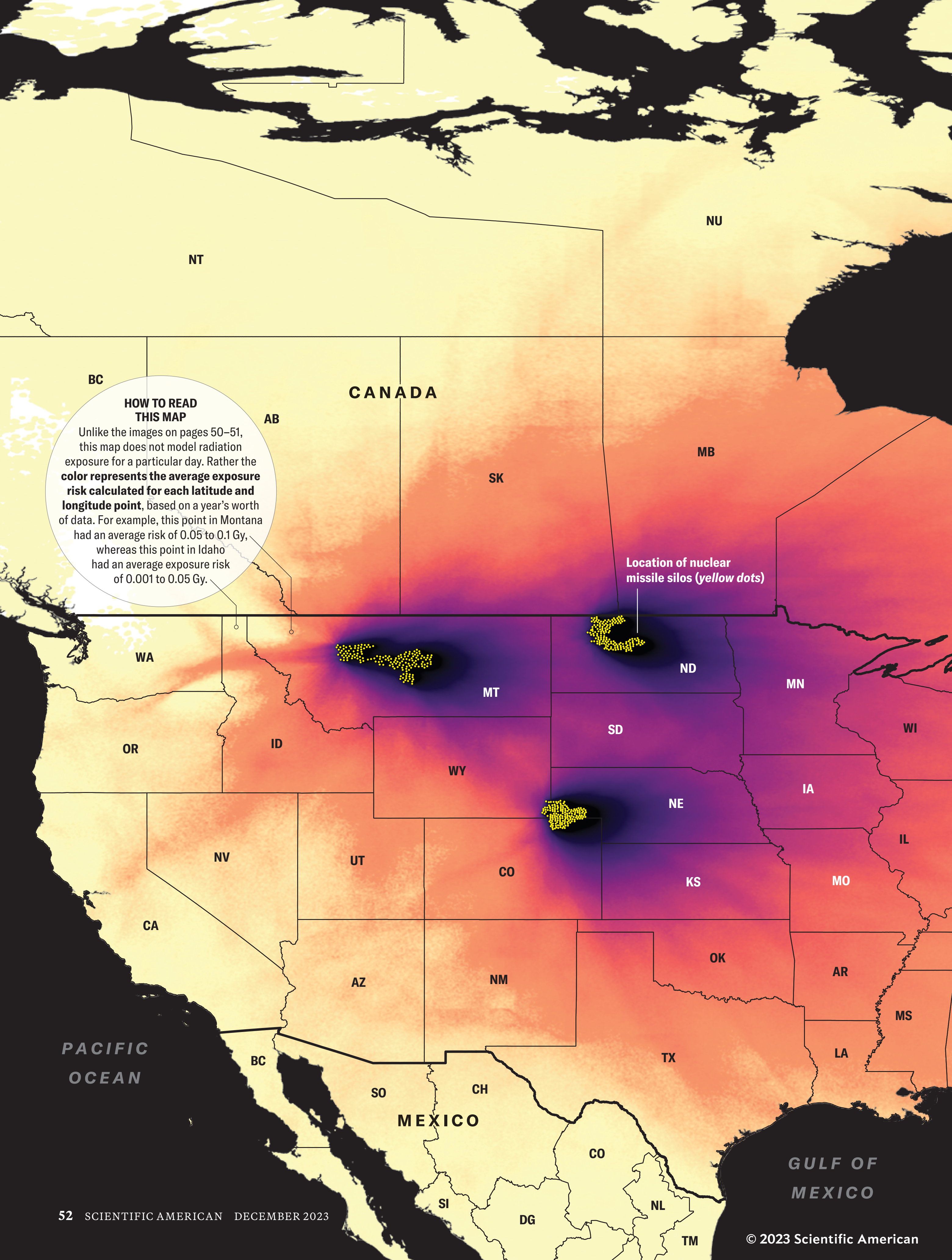


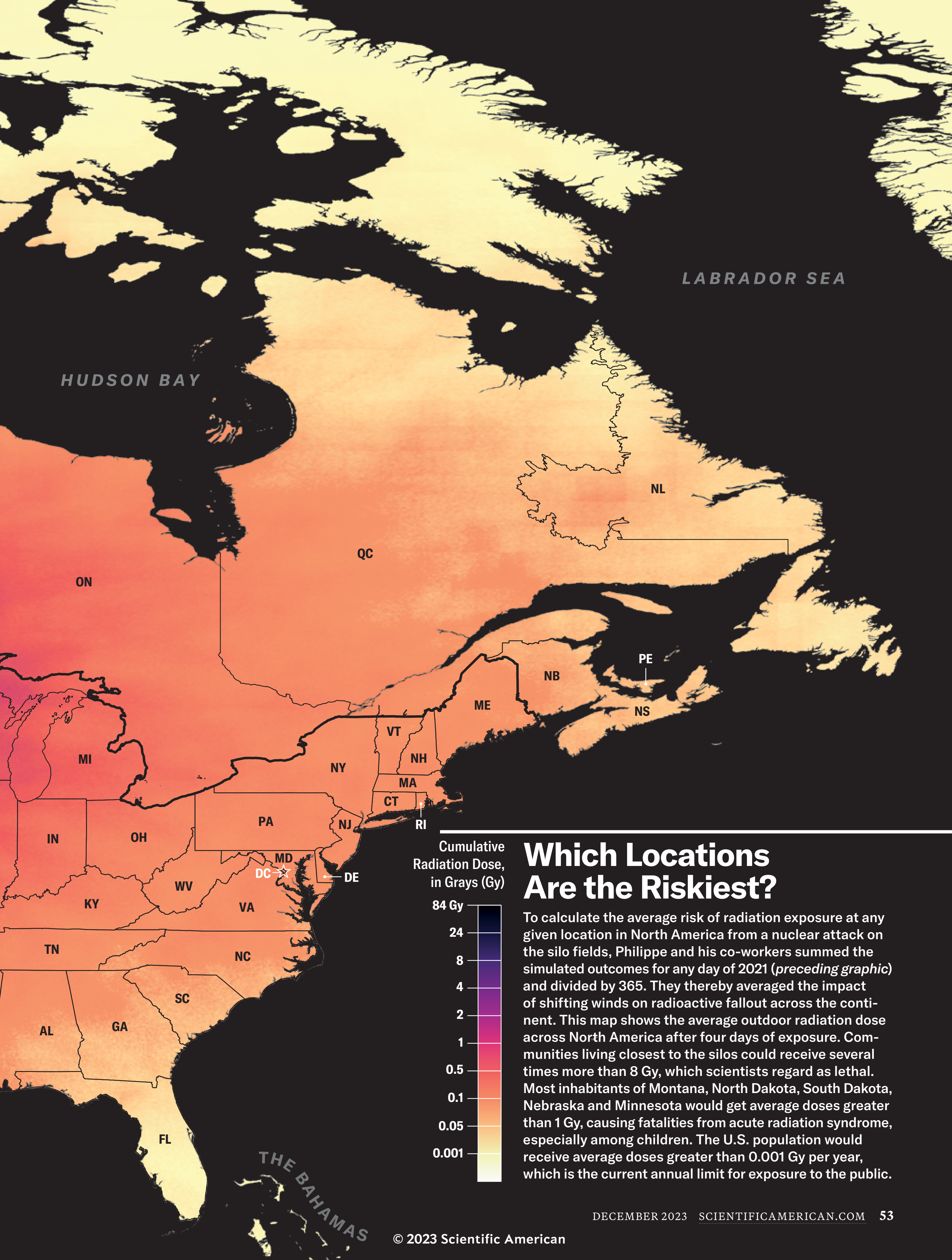


FATALITY COUNT
For a simulated attack on any day of 2021, the scientists computed the resulting fatalities. The chart (*right*) shows the impact of variable wind directions on the estimated fatalities after four days of exposure. The estimates range from 340,000 (for an attack on July 1) to 4.6 million (on December 2). The average estimated death toll is 1.4 million. The curve (*far right*) shows the probability (technically, probability density) of the number of fatalities specified on the vertical axis.



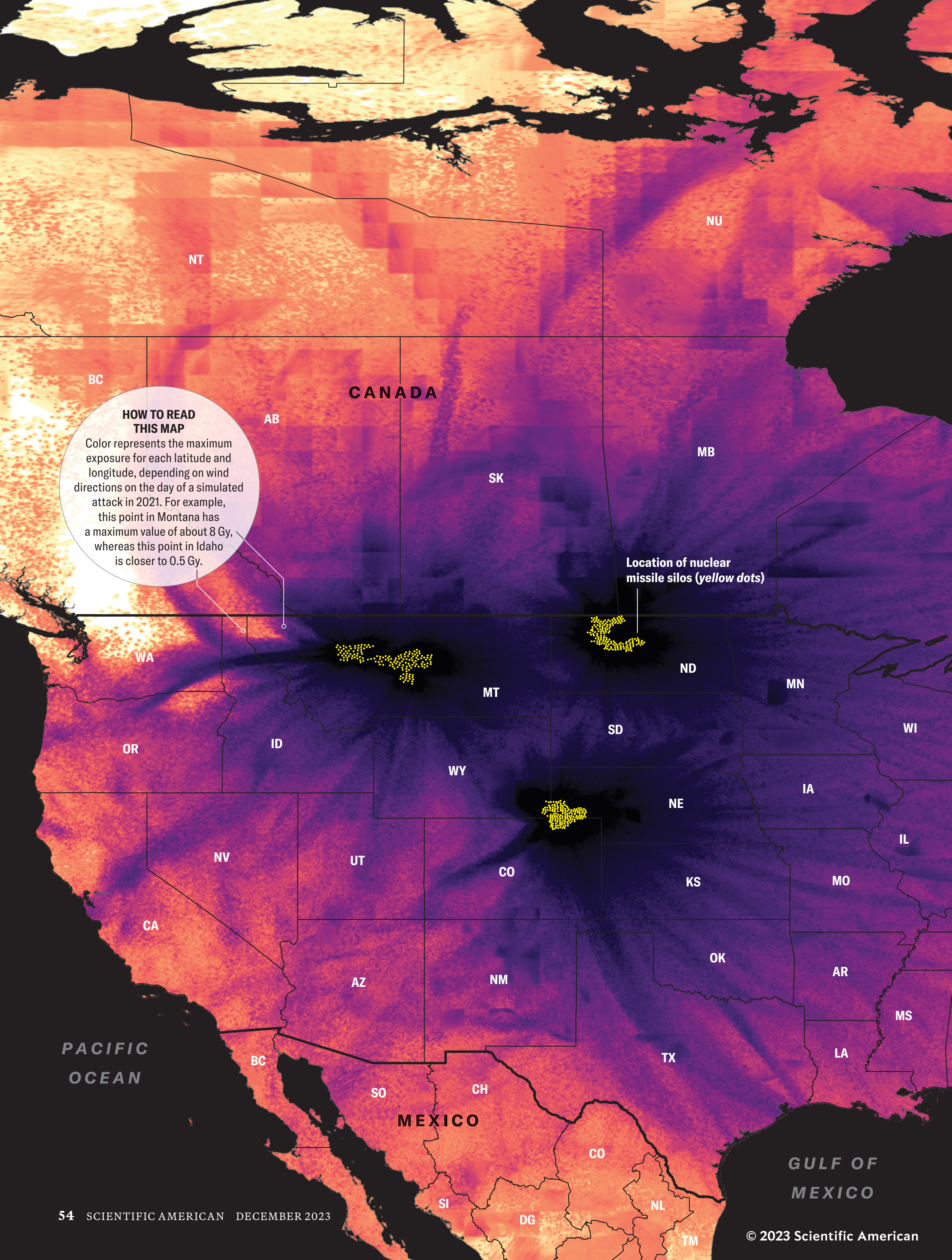



HOW TO READ THIS MAP
Unlike the images on pages 50–51, this map does not model radiation exposure for a particular day. Rather the **color represents the average exposure risk calculated for each latitude and longitude point**, based on a year's worth of data. For example, this point in Montana had an average risk of 0.05 to 0.1 Gy, whereas this point in Idaho had an average exposure risk of 0.001 to 0.05 Gy.
Location of nuclear missile silos (*yellow dots*)
CANADA
NT
NU
BC
AB
SK
MB
WA
OR
ID
MT
ND
SD
MN
WI
WY
NE
IA
IL
NV
UT
CO
KS
MO
CA
AZ
NM
OK
AR
MS
TX
LA
PACIFIC OCEAN
GULF OF MEXICO
MEXICO
BC
SO
CH
CO
SI
DG
NL
TM



Which Locations Are the Riskiest?

To calculate the average risk of radiation exposure at any given location in North America from a nuclear attack on the silo fields, Philippe and his co-workers summed the simulated outcomes for any day of 2021 (*preceding graphic*) and divided by 365. They thereby averaged the impact of shifting winds on radioactive fallout across the continent. This map shows the average outdoor radiation dose across North America after four days of exposure. Communities living closest to the silos could receive several times more than 8 Gy, which scientists regard as lethal. Most inhabitants of Montana, North Dakota, South Dakota, Nebraska and Minnesota would get average doses greater than 1 Gy, causing fatalities from acute radiation syndrome, especially among children. The U.S. population would receive average doses greater than 0.001 Gy per year, which is the current annual limit for exposure to the public.


NT
NU
BC
CANADA
AB
SK
MB
HOW TO READ THIS MAP
Color represents the maximum exposure for each latitude and longitude, depending on wind directions on the day of a simulated attack in 2021. For example, this point in Montana has a maximum value of about 8 Gy, whereas this point in Idaho is closer to 0.5 Gy.
Location of nuclear missile silos (*yellow dots*)
WA
MT
ND
MN
OR
ID
SD
WI
WY
NE
IA
NV
UT
CO
KS
IL
MO
CA
OK
AZ
NM
AR
MS
PACIFIC OCEAN
BC
TX
LA
SO
CH
MEXICO
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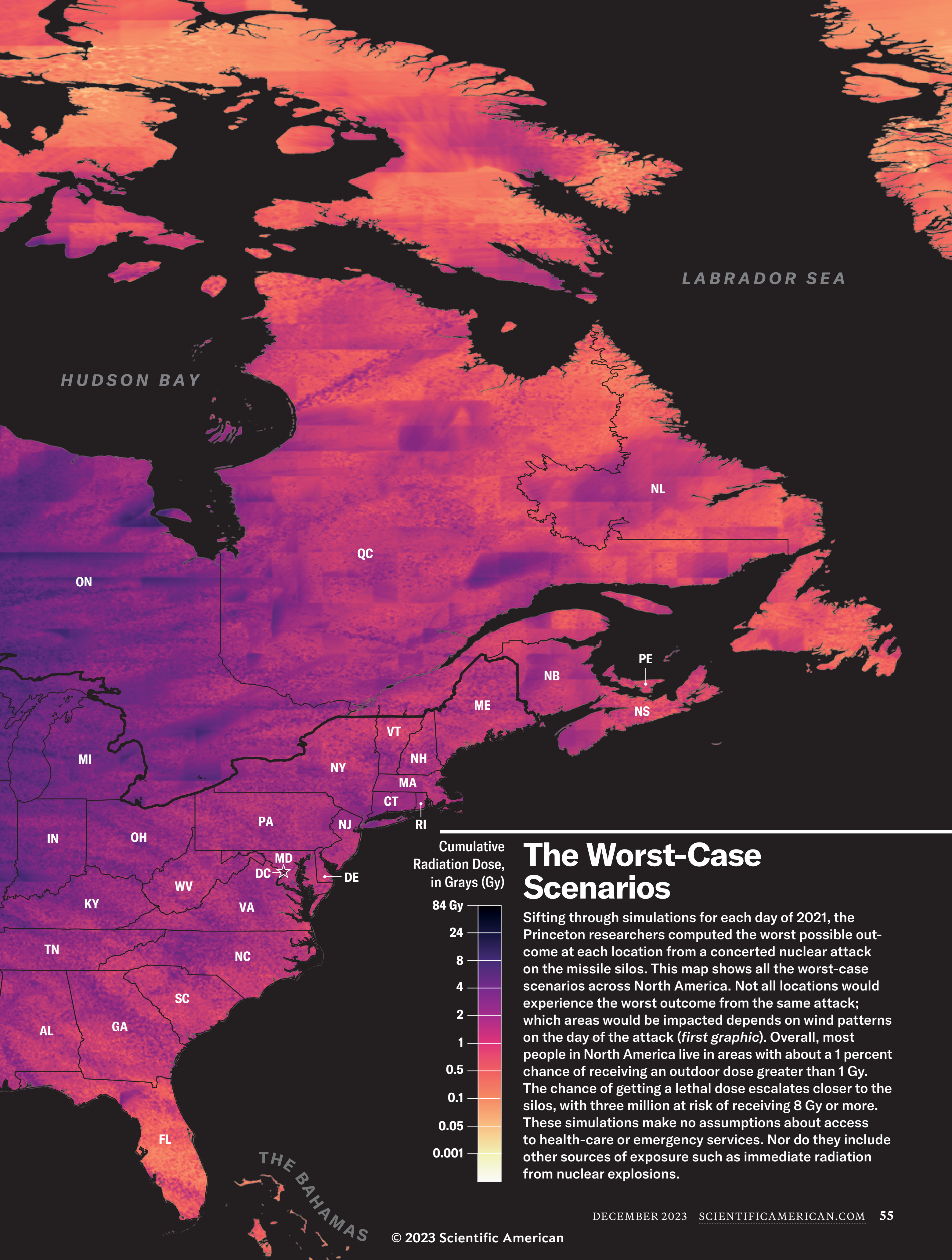
GULF OF MEXICO
SI
DG
NL
TM



The Worst-Case Scenarios

Sifting through simulations for each day of 2021, the Princeton researchers computed the worst possible outcome at each location from a concerted nuclear attack on the missile silos. This map shows all the worst-case scenarios across North America. Not all locations would experience the worst outcome from the same attack; which areas would be impacted depends on wind patterns on the day of the attack (*first graphic*). Overall, most people in North America live in areas with about a 1 percent chance of receiving an outdoor dose greater than 1 Gy. The chance of getting a lethal dose escalates closer to the silos, with three million at risk of receiving 8 Gy or more. These simulations make no assumptions about access to health-care or emergency services. Nor do they include other sources of exposure such as immediate radiation from nuclear explosions.

EDUCATION

Misdiagnosing

Dyslexia

How a flawed formula deprives children of help with reading

BY SARAH CARR

ILLUSTRATION BY MELINDA BECK

IT PAINS TIM ODEGARD that four decades after a misguided approach to diagnosing dyslexia kept him from getting help in school, thousands of children across the U.S. are needlessly suffering for the same reason.

During the initial weeks of first grade Odegard's struggles with reading went undetected as he memorized words that classmates read aloud before him. The strategy worked so well that his teacher moved him to the position of "first reader." It then became apparent that the six-year-old not only wasn't the strongest reader in the class—he couldn't read at all. The teacher dispatched him to a low-skill group. "It just kind of went downhill from there," Odegard, now 47, recalls.

Through sheer determination and reliance on his prodigious memory, Odegard eventually memorized enough words to get by and earned decent grades, although they would never come easily. "I compensated for my reading and spelling problems by staying up until 1 or 2 A.M. to get things done," he says. He never received extra help or special education services from his Houston-area school district. Instead a couple of teachers seemed to doubt his intelligence. When Odegard was the first student in his school to solve a complex murder mystery puzzle, one of them said he must have guessed.

It wasn't until he was in his late 20s that Odegard came to understand why his teachers thought so poorly of his abilities. In 2004, as a new Ph.D., he told his mother that the National Institutes of Health had awarded him a postdoctoral fellowship to study dyslexia, a condition he'd long suspected he had. She shared that when he was in third grade, school officials had used a so-called discrepancy model that compared intelligence quotient (IQ) with reading performance to rule that he didn't have a learning disability.

"I was thought to be too stupid to be dyslexic," says Odegard, now editor in chief of the *Annals of Dyslexia* and chair of excellence in dyslexic studies at Middle Tennessee State University in Murfreesboro, Tenn.

Up to around 20 percent of the U.S. population has dyslexia, a neurological condition that makes it difficult to decipher and spell written words. Someone with the disability might omit short words such as "and" and "the" while reading aloud, for example, or read "dog" as "god"—even if they speak normally in conversation. The condition impedes a person's ability to process written information and can negatively impact their career and well-being. Yet only a fraction of affected students get a dyslexia diagnosis or the specialized assistance that can help them manage their difficulty reading.

One reason so many diagnoses are missed is that thousands of schools in the U.S. continue to use an iteration of the discrepancy model to test children for learning disabilities. Moreover, for a multitude of reasons, including biases in IQ tests, a disproportionate number of those diagnosed—and helped—have been white and middle- to upper-class. "It's unfair, it's discriminatory, and it disadvantages already economically disadvantaged kids," says Jack Fletcher, co-founder of the Texas Center for Learning Disabilities in Houston and one of the first scientists to question the discrepancy model's validity.

The model has shaped decades of policy regarding whose literacy is considered vital and worthy of extra help and investment—and whose is not. It is rooted in long-standing misconceptions about dyslexia. Reforming how the condition is defined and diagnosed could help many more children learn to read.

Sarah Carr is a New York–based journalist who covers education. She is author of *Hope against Hope* (Bloomsbury Press, 2013), about the New Orleans schools after Hurricane Katrina.

SPEAKING COMES NATURALLY to most children, being a gift of human evolution, but reading and writing are inventions that must be consciously and painstakingly learned. No one is born with neural circuits for connecting the sounds of speech to squiggles on paper. Instead when someone learns to read, their brain improvises, splicing and joining sections of preexisting circuits for processing vision and speech to form a new "reading circuit." To read the (written) word "dog," for example, a typical brain will disaggregate the word into its constituent letters, "d," "o" and "g," and then summon from memory the sound fragments, or phonemes, associated with each letter. It aggregates these phonemes into the sound "dog" and retrieves the meaning of the word that matches that sound. Most brains eventually learn to do all these steps so fast that the action seems automatic. Some written words become so familiar that the speech circuit eventually gets bypassed, so that there is a direct association between the word as seen on paper or on a screen and its meaning.

Because human brains are organized in diverse ways, some people's reading circuits end up being inefficient. Dyslexia is the most common reading disability. People with the condition, which is partly linked to genetics, often have less gray matter and brain activity in the parietotemporal region of the brain's left hemisphere, associated with connecting the sounds of speech to the shapes of printed text.

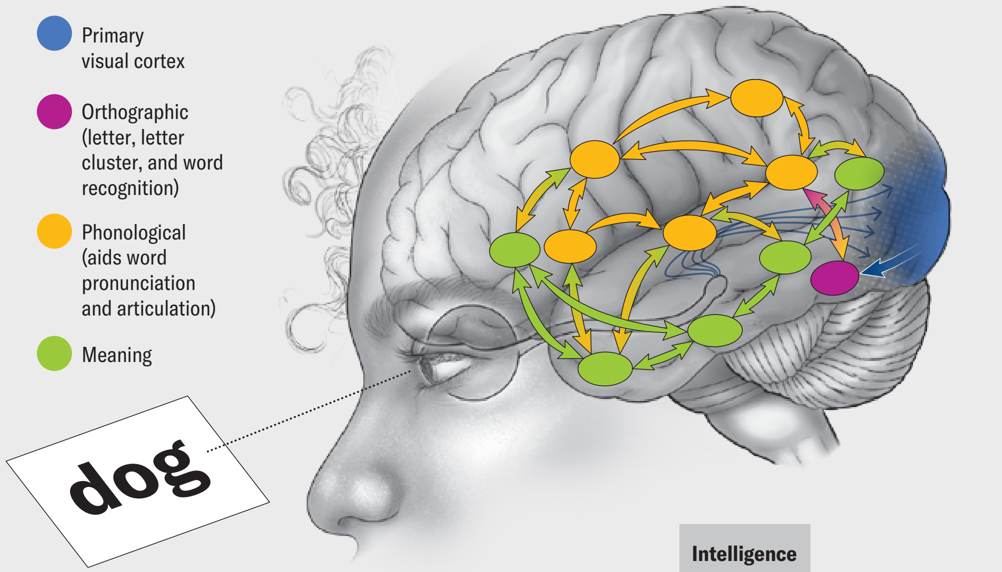
The severity and manifestations of dyslexia can vary from person to person, but children with the learning disability benefit most from early help with explications of the sound structures underlying words. For those who continue to struggle in school, the ideal instruction is one-on-one or in a small group with a trained teacher who provides intensive and systematic assistance in making connections between written words and sounds. Learning the rules—and the many, many exceptions—of the English language is particularly important because children with dyslexia are typically unable to pick them up through mere exposure to

Dyslexia and the Brain

Evolution has gifted humans with neural circuits for seeing and speaking, but reading has no such in-built circuits. To learn to read, the brain must concoct a new circuit by linking the existing vision and speech circuits with those encoding meaning. Most people with dyslexia, a condition that makes it difficult to read and spell written words, can learn these skills with the right instruction.

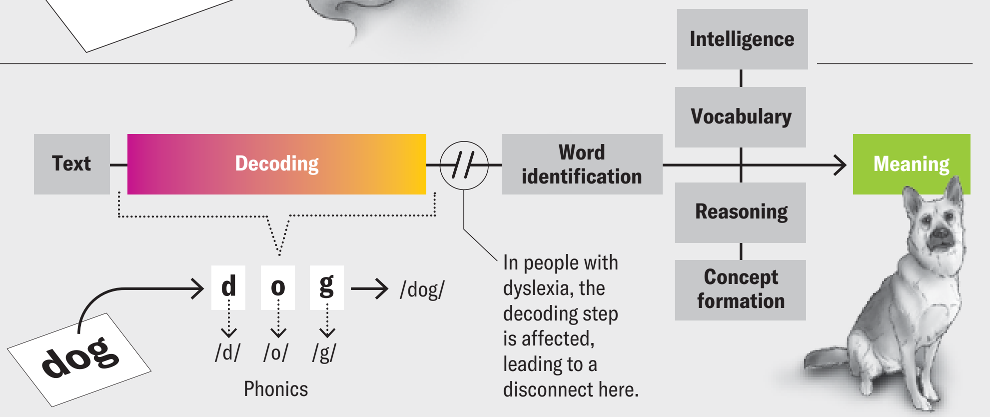
THE "READING" CIRCUIT

Seeing a written word activates the primary visual cortex. The region alerts the orthographic area, which recognizes the letters and the word, if these have already been learned. A "phonological" circuit connects the letters and the word with the corresponding sounds. Finally, the meaning circuit extracts the meaning of the word, depending on the context. For some readers, the orthographic area may connnect directly to the meaning processor, bypassing the phonological, or speech, circuit.



A DISRUPTED CIRCUIT

People with dyslexia have problems with their orthographic and phonological processors. They find it difficult to disaggregate a word into its component letters, associate the letters with the correct sounds, and reassemble them into the corresponding spoken word to extract its meaning from the meaning circuit.



Source: *Reading in the Brain*, by Stanislas Dehaene. Penguin Books, 2010 (*brain diagram reference*)

text. The letter "a" can be pronounced five different ways in English, whereas in Spanish, for instance, vowels almost always have the same pronunciation.

With the right kind of instruction, most children with dyslexia can learn how to read. In part because of an accident of scientific history, however, this essential assistance has been far more available to kids who score higher on IQ and other cognitive tests. An early case report of dyslexia, published in the *British Medical Journal* in 1896, helped to define the disorder as an unexpected deficit in otherwise "bright" children. The study described a 14-year-old referred to as Percy F. "He has always been a bright and intelligent boy, quick at games, and in no way inferior to others," wrote the doctor who examined Percy, "yet in writing from dictation he comes to grief over any but the simplest words."

That incipient definition characterized a lot of early thinking about dyslexia. It was inadvertently codified in school systems through influential studies led by British psychiatrists Michael Rutter and William Yule on the Isle of Wight in the 1960s and early 1970s. Rutter and Yule are well regarded for being among the first in the field to focus deeply on children and for their groundbreaking work in autism and post-traumatic stress disorder. When devising a definition of "reading disability" based on the population of nine- to 11-year-olds on the island, the researchers distinguished between poor readers who read at levels predicted by their IQs and those who did not, looking for evidence of dyslexia only in those in the latter group. The studies came just as the U.S. was creating its own special education categories and definitions to prepare for the passage of the Education for All Handicapped Children Act (EAHCA) in 1975. When it came to learning disabilities, experts relied heavily on the idea that for a learning disability to be present, reading performance had to fall short of IQ.

Guidelines put out by the U.S. government in 1977 asked that schools look for a "severe discrepancy between levels of ability and achievement" when screening children for learning disabilities. Thus, a child's IQ scores, which rank cognitive abilities such as reasoning, began to play an outsize role in determining countless students' educational fates. Specifically, if the IQ score wasn't high enough and, in consequence, the gap wasn't big enough, the child wasn't diagnosed with a reading disability. Despite the fact that most youngsters can learn to read regardless of their IQ score, those with lower scores were often assumed to lack the "smarts" to read well.

Graphic by Body Scientific

An IQ test kept Sandra Chittenden's daughter from getting the right help for years. The girl learned new words slowly and struggled to pronounce them correctly, mixing up similar-sounding words. In kindergarten she had no interest in letters and sounds, and she couldn't easily see the similarities and differences across words on a page. Having a mild form of dyslexia herself and with an older son who is severely dyslexic, Chittenden, who is a special education advocate, asked the school district to evaluate the girl for a reading disability.

The five-year-old was promptly given an IQ test. She posted an average overall score and a below-average score on a reading achievement test. But the gap between the two scores didn't meet the cutoff of 15 points, so the girl was not given appropriate reading services in her Vermont school. The same thing happened when Chittenden requested another evaluation when her daughter was in first grade.

For the child, the results were wounding. During her first couple of years of elementary school "her nervous system was like a pressure cooker because she wasn't being given appropriate help," Chittenden says. "She held it together all day at school and then would explode." In third grade the girl was diagnosed with a learning disability in math, and the school added a dyslexia diagnosis because of her continued struggles with both arithmetic and reading. But for years, Chittenden says, "I remember it being really frustrating knowing my child had dyslexia and not being able to get the right help."

As of this year, partly in response to parental concerns, Vermont is no longer using the discrepancy model to diagnose learning disabilities.

RESEARCHERS POINTED OUT problems with the discrepancy model even before its use became prevalent in the U.S. Fletcher, an early critic, noted a methodological issue in the Isle of Wight studies: they did not exclude children with intellectual disabilities or brain injuries. Yet by some accounts there was an unusually large number of neurologically impaired subjects on the island at the time, resulting in a skewed sample.

It has also long been clear that IQ tests can be biased against Black or low-income students, as well as many others, because they contain language and content that is more familiar to white middle- and upper-income students. Researchers began to observe inequitable results in the late 1970s as American public schools began evaluating more children to comply with the mandates for the EAHCA, since renamed the Individuals with Disabilities Education Act. As a research assistant at the University of Minnesota, Mark Shinn saw how the discrepancy model disproportionately prevented children from low-income families, first-time English learners and students of color from getting help. "You had all these kids in high-poverty schools with [below average] cognitive ability of 90 and 80, and the schools could throw up their hands and say, 'They are too "slow" to benefit [from services],'" recalls Shinn, now a professor emeritus of school psychology at National Louis University in Chicago. Yet "it was well known that poor kids ... earned low scores on cognitive tests largely because of a lack of opportunities and experiences."

In the 1980s educational psychologist Linda Siegel, now an emeritus professor at the University of British Columbia, began investigating some of these anecdotal suspicions. In an influential 1994 publication, she noted that the main distinction between children with a reading disability and those without was not their IQs but the way their minds processed written words. "The basic assumption that underlies decades of classification in research and educational practice regarding reading disabilities is becoming increasingly untenable," she and her co-author wrote. In the same issue of the *Journal of Educational Psychology,* Fletcher and his colleagues observed that the "cognitive profiles" of poor readers who met the discrepancy definition and of those who didn't were more similar than different. The key to diagnosing reading disabilities, they wrote, would be to instead measure "deficiencies in phonological awareness," the ability to recognize and work with phonemes in spoken language.

Since then, the scientific consensus against the discrepancy model has grown. One study found that regardless of their IQ, poor readers benefit from specialized reading instruction and support at statistically identical levels. Another used magnetic resonance imaging to show the same reduced brain-activation patterns in the left hemisphere (compared with those of typical readers) in weak school-age readers who were asked whether two written words rhymed—regardless of whether the weak readers met discrepancy criteria. Neuroscientist Fumiko Hoeft, who supervised the study at Stanford University's Center for Interdisciplinary Brain Sciences Research, says it bolsters the idea that the discrepancy method makes an arbitrary distinction among different groups of poor readers. In fact, "dyslexia can occur in people of high, middle and low cognitive abilities," notes Nadine Gaab, an associate professor at the Harvard Graduate School of Education.

By the 2000s ample scientific evidence indicated the arbitrariness of IQ's use as a basis for a dyslexia diagnosis. And there were mounting concerns that the discrepancy model was fundamentally racist and classist: it disproportionately prevented low-income children and children of color from getting help with learning disabilities. In 2004 the federal government reversed course on its 1970s guidance, strongly recommending that states consider alternatives. "I would... encourage this commission to drive a stake through the heart of this overreliance on the discrepancy model for determining the kinds of children that need services," psychologist Wade Horn, then U.S. assistant secretary for children and families, told a panel of experts tasked with revising special education law in the early 2000s. "I've wondered for 25 years why it is that we continue to use it."

But a 2018 study found that about one third of school psychologists were still using the discrepancy model to screen students for learning disabilities. And although most contemporary specialists concur that dyslexia is unrelated to intelligence, many of the most widely used definitions still refer to it as an "unexpected" disorder. "These definitional issues are not trivial, because they drive research, they drive funding, they drive assessment, they drive everything," says Julie Washington, a professor in the School of Education at the University of California, Irvine, whose research focuses on the intersection of language, literacy and poverty in African American children.

Even as more states and school districts move away from the discrepancy model, many researchers are concerned that they too often are replacing it with an equally problematic system. Often referred to as patterns of strengths and weaknesses or by Odegard as "discrepancy 2.0," this method continues to rely heavily on cognitive tests and still calls for significant gaps between ability and performance for a student to qualify as having a learning disability. "Schools still want simple formulas and put way too much emphasis on the testing," Fletcher says.

TWICE IN ELEMENTARY SCHOOL, Texas student Marcelo Ruiz, who lives just north of Houston, was denied a dyslexia diagnosis because of "discrepancy 2.0." He had high cognitive scores, but evaluators said he did not show skill gaps in the areas he needed to qualify as dyslexic. School got harder and harder for Ruiz, and in high school he was still inverting letters and having trouble with reading. In the fall of 2022, his senior year, the teenager finally got a dyslexia diagnosis, but by then it was far too late to give him the help he had long craved. Because of his mediocre grades, Ruiz says, he had difficulty getting admitted into four-year colleges; he is currently at a community college and hoping to transfer. "Growing up, I felt stupid," the 18-year-old says. "My grades kept going down, and I didn't know what was wrong with me. It was really demotivating not knowing what I had and what you could do for it, not being able to get help."

According to several researchers, a better—though hardly perfect—approach to assessing children for learning disabilities is "response to intervention," or RTI. In this method, teachers intervene early with struggling readers and monitor how they respond to help, making a referral for special education services after what one research paper dubbed a "student's failure to respond to treatment." Some states already require exclusive use of RTI, although it can be hard to implement because teachers have to be well trained in what interventions to administer and how to determine whether they are working. When teachers do make a referral for special education services, there's often still a question of how—and whether—to make a learning disability determination.

For this reason, some experts in the field say they would like to see more no-cost or low-cost access to the kind of testing that qualified neuropsychologists do: assessing a child's capacity for and speed at the many components that make up successful reading. (One bill pending in New York State would mandate that private health-care plans pay for neuropsychological exams focused on dyslexia.) The specifics can look quite different for a seven-year-old than for a high school student, Gaab explains. But generally, experts say testing should be used to gauge such skills as a child's ability to recognize "sight words" (common words that often come up in reading), to detect "nonsense" words that follow the rules of the English language but are not actual words, and to read under timed conditions and spell words correctly in their writing.

It isn't out of the question for school districts to do this type of testing on their own—and some of the best-resourced ones already do, or they contract with an outside neuropsychologist. But for most school psychologists, it would represent a departure from decades of training and practice focused on the administration of IQ and cognitive tests. The discrepancy model is "easier" because a child either meets the cutoff or doesn't. "It reminds me of leeching blood," says Tiffany Hogan, a professor and director of the Speech & Language Literacy Lab at the MGH Institute of Health Professions in Boston. "They did that for a long time knowing it wasn't the best way, but there was no replacement."

Another, largely overlooked reason for the continued prevalence of discrepancy-based testing may be that the families most hurt by it are the least powerful in terms of their influence over public school practice and policy. Many schools feel pressure, both covert and overt, to not identify children with dyslexia because there aren't enough specialists or teachers trained to work with them. Families with money, power and privilege can negotiate with the district more effectively to meet their child's needs or hire an advocate or lawyer to lobby on their behalf. If diagnosis and help still remain elusive, they can pay for private neuropsychological exams, which can cost thousands of dollars. They also can, and often do, circumvent the public system entirely by hiring private reading tutors or sending their children to private schools focused on reading remediation. (Often these schools also use the discrepancy model to determine whom to admit.) For all these reasons, as well as the discrepancy model's bias favoring high IQ scores, dyslexia has long had a reputation as a "privileged" diagnosis.

The dyslexia advocacy community has in some states also been predominantly white and financially privileged, with low-income families and parents of color more likely to fear the stigma of a disability diagnosis. "Historically, we don't talk about learning disabilities and mental health in the Black community because there's a stigma and shame attached to it," says Winifred Winston, a Baltimore mother who hosts the *Black and Dyslexic* podcast. "Enslaved people could not show any sign of weakness or perceived weakness. So we have a history of being 'okay' ... when we are in fact not okay or do require assistance."

Partly through the leadership of parents such as Winston, that's changing as more families learn about reading disabilities and the extra support a diagnosis can bring.

NOW 71 AND 81, RESPECTIVELY, Jack Fletcher and Linda Siegel are still fighting to get children equal access to essential help in learning how to read. They are part of a broad-based effort seeking to strengthen access to general reading instruction for all so that fewer students get held back by learning disabilities or need intensive reading remediation. Many states are doing just that, with a growing number passing legislation promoting the "science of reading," which emphasizes explicit and systematic instruction in phonics. Early screening for language challenges in the youngest grades is also key.

Still, Tim Odegard says he regularly hears from families frustrated that their kids were disqualified from reading services for the same reason he was: testing determined that they are not "smart" enough to be dyslexic.

Over the years, Odegard says, some colleagues and friends have remarked that, given his success, the experience must have made him stronger—a characterization he resents. "It wasn't a gift," he says. "I don't see any of those challenges of having to stay up later and work five times harder as helpful." Growing up, "I had a huge chip on my shoulder."

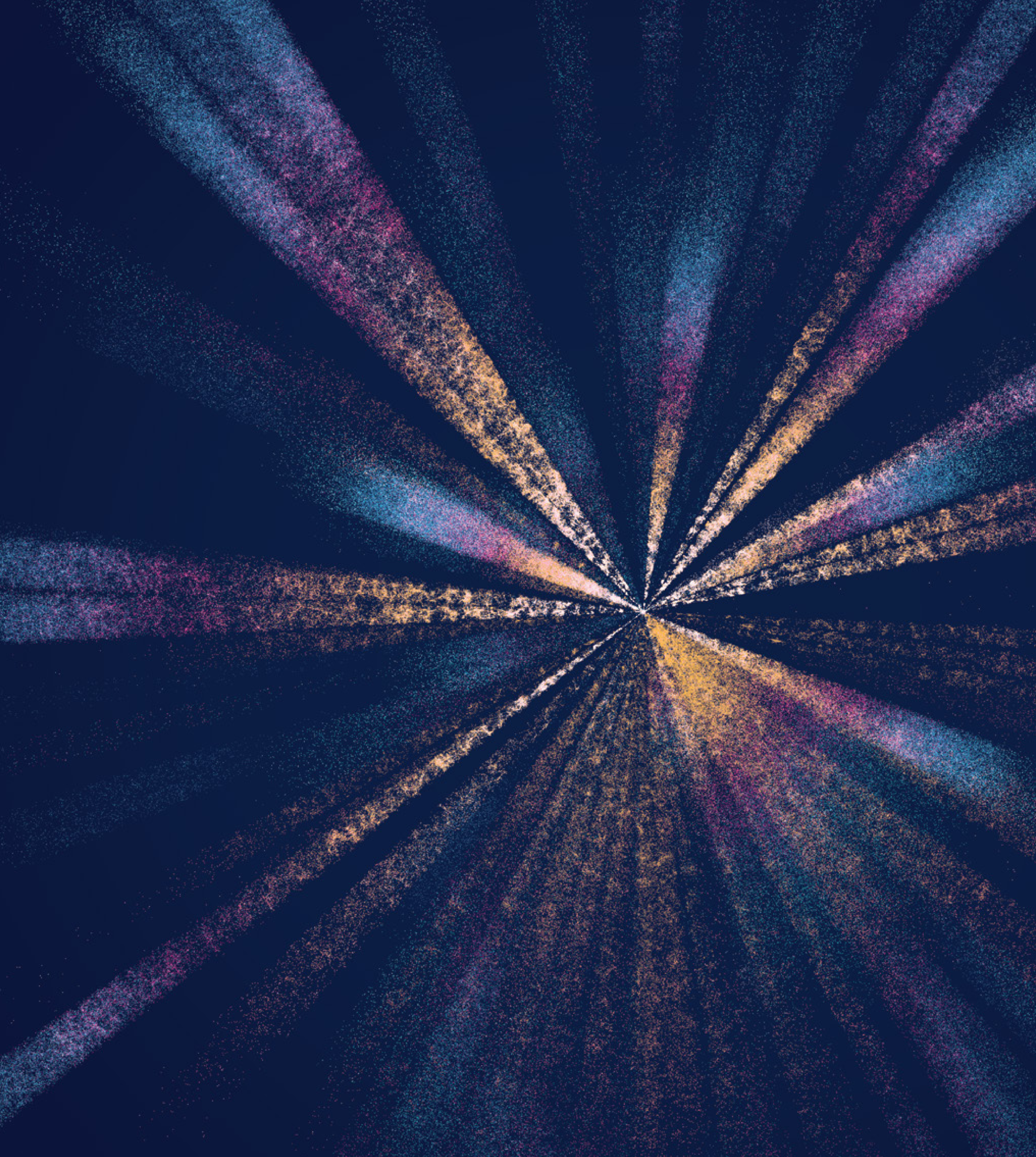
On reflection, though, Odegard says there was perhaps one benefit to his early educational struggles. "If there was any gift I got from dyslexia, it was to have a lot of compassion and empathy," he asserts, "because I could never hide in that school that I couldn't read and spell." That early feeling of powerlessness fueled his interest in studying child psychology in college and graduate school, he says: "My own loss of agency and helplessness led me to want to find a way to give children a voice." ⬢

This story was produced with the Hechinger Report, a nonprofit, independent news organization focused on inequality and innovation in education.

FROM OUR ARCHIVES

The Advantages of Dyslexia. Matthew H. Schneps; *Scientific American Mind,* January 2015.
ScientificAmerican.com/magazine/sa

The Dark Energy Spectroscopic Instrument (DESI) will spend five years creating a 3-D map of the universe that will help reveal the nature of the dark energy driving cosmic expansion. The project's first six months of data show slivers of the universe that represent just 1 percent of the survey's ultimate volume of space. The colors represent different types of galaxies, including nearby bright galaxies in yellow, luminous red galaxies in magenta and galaxies with supermassive black holes in turquoise.



The Cosmic Surprise

Scientists discovered dark energy 25 years ago. They're still trying to figure out what it is

BY RICHARD PANEK
GRAPHIC BY NADIEH BREMER

ONE AFTERNOON IN EARLY 1994 a couple of astronomers sitting in an air-conditioned computer room at an observatory headquarters in the coastal town of La Serena, Chile, got to talking. Nicholas Suntzeff, an associate astronomer at the Cerro Tololo Inter-American Observatory, and Brian Schmidt, who had recently completed his doctoral thesis at the Center for Astrophysics | Harvard & Smithsonian, were specialists in supernovae—exploding stars. Suntzeff and Schmidt decided that the time had finally come to use their expertise to tackle one of the fundamental questions in cosmology: What is the fate of the universe?

Richard Panek is the recipient of a Guggenheim Fellowship in Science Writing. He is the prizewinning author of *The 4% Universe* (Houghton Mifflin Harcourt, 2011). His next book, *Pillars of Creation*, the story of the James Webb Space Telescope, is forthcoming from Little, Brown.

Specifically, in a universe full of matter that is gravitationally attracting all other matter, logic dictates that the expansion of space—which began at the big bang and has continued ever since—would be slowing. But by how much? Just enough that the expansion will eventually come to an eternal standstill? Or so much that the expansion will eventually reverse itself in a kind of about-face big bang?

They grabbed the nearest blue-and-gray sheet of IBM printout paper, flipped it over and began scribbling a plan: the telescopes to secure, the peers to recruit, the responsibilities to delegate.

Meanwhile some 9,600 kilometers up the Pacific Coast, a collaboration at Lawrence Berkeley National Laboratory in California, operating under the leadership of physicist Saul Perlmutter, was already pursuing the same goal, using the same supernova approach and relying on the same underlying logic. Suntzeff and Schmidt knew about Perlmutter's Supernova Cosmology Project (SCP). But they also knew that the SCP team consisted primarily of physicists who, like Perlmutter himself, were learning astronomy on the fly. Surely, Schmidt and Suntzeff reassured each other, a team of actual astronomers could catch up.

And their team did, just in time. In 1998 the rival collaborations independently reached the same conclusion as to how much the expansion of the universe is slowing down: it's not. It's speeding up.

This year marks the 25th anniversary of the discovery of evidence for "dark energy"—a moniker for whatever is driving the acceleration that even then meant next to nothing yet encompassed nearly everything. The coinage was almost a joke, and the joke was on us. If dark energy were real, it would constitute two thirds of all the mass and energy in the universe—that is, two thirds of what people had always assumed, from the dawn of civilization onward, to be the universe in its entirety. Yet what that two thirds of the universe was remained a mystery.

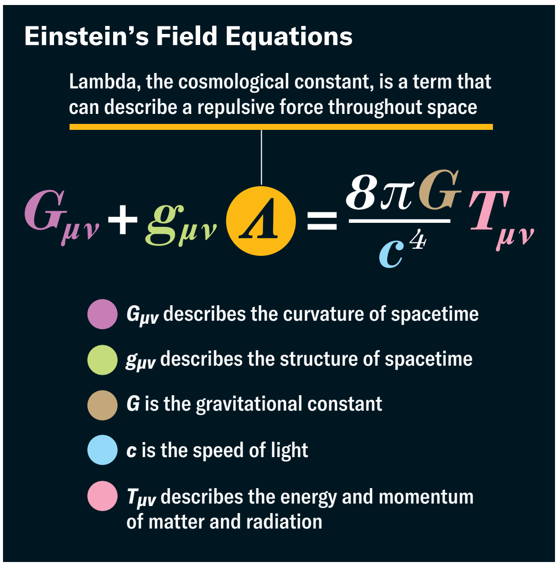
A quarter of a century later that summary still applies. Which is not to suggest, however, that science has made no progress. Over the decades observers have gathered ever more convincing evidence of dark energy's existence, and this effort continues to drive a significant part of observational cosmology while inspiring ever more ingenious methods to, if not detect, at least define it. But right from the start—in the first months of 1998—theorists recognized that dark energy presents an existential problem of more immediate urgency than the fate of the universe: the future of physics.

THE MYSTERY OF WHY a universe full of matter gravitationally attracting all other matter hasn't yet collapsed on itself has haunted astronomy at least since Isaac Newton's introduction of a universal law of gravitation. In 1693, only six years after the publication of his *Principia,* Newton acknowledged to an inquiring

Source: "The Early Data Release of the Dark Energy Spectroscopic Instrument," by DESI Collaboration et al.; 2023 (*data*) (*preceding pages*) cleric that positing a universe in perpetual equilibrium is akin to making "not one Needle only, but an infinite number of them (so many as there are particles in an infinite Space) stand accurately poised upon their Points. Yet I grant it possible," he immediately added, "at least by a divine Power."

"It was a great missed opportunity for theoretical physics," the late Stephen Hawking wrote in a 1999 introduction to a new translation of *Principia*. "Newton could have predicted the expansion of the universe."

So, too, Einstein. When, in 1917, he applied his equations for general relativity to cosmology, he confronted the same problem as Newton. Unlike Newton, though, Einstein added to the equation not a divine power but the Greek symbol lambda (Λ), an arbitrary mathematical shorthand for whatever was keeping the universe in perfect balance.

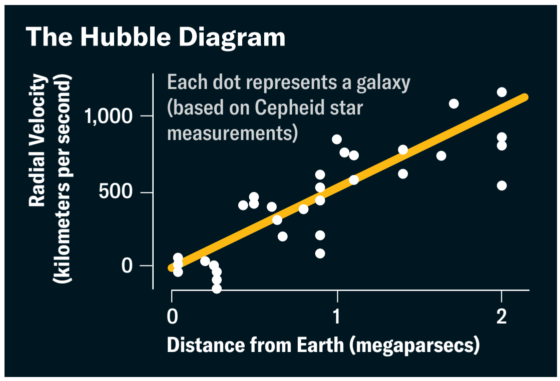


The following decade astronomer Edwin Hubble seemingly rendered lambda superfluous through his twin discoveries that other "island universes," or galaxies, exist beyond our own Milky Way and that on the whole those galaxies appear to be receding from us in a fairly straightforward manner: the farther, the faster—as if, perhaps, the universe had emerged from a single explosive event. The 1964 discovery of evidence supporting the big bang theory immediately elevated cosmology from metaphysics to hard science. Only six years later, in an essay in *Physics Today* that set the agenda for a generation, astronomer (and onetime Hubble protégé) Allan Sandage defined the science of big bang cosmology as "the search for two numbers." One number was "the rate of expansion" now. The second was the "deceleration in the expansion" over time.

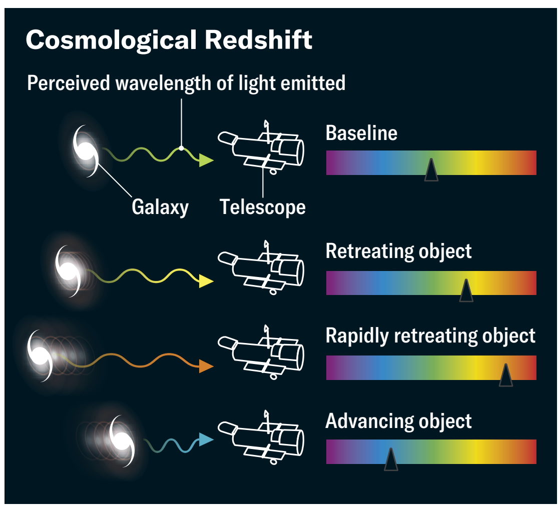
Decades would pass before the first real investigations into the second number got underway, but it was no coincidence that two collaborations more or less simultaneously started work on it at that point. Only then had advances in technology and theory made the search for the deceleration parameter feasible.

In the late 1980s and early 1990s the means by which astronomers gather light was making the transition from analog to digital—from photographic plates, which could collect about 5 percent of the photons that hit them, to charge-coupled devices, which have a photon-collection rate upward of 80 percent. The greater a telescope's light-gathering capacity, the deeper its view across the universe—and deeper and deeper views across space and (because the speed of light is finite) time are what a search for the expansion rate of the universe requires.

The Hubble diagram, as cosmologists call the graph Hubble used in determining that the universe is expanding, plots two values: the velocities with which galaxies are apparently moving away from us on one axis and the distances of the galaxies from us on the other.



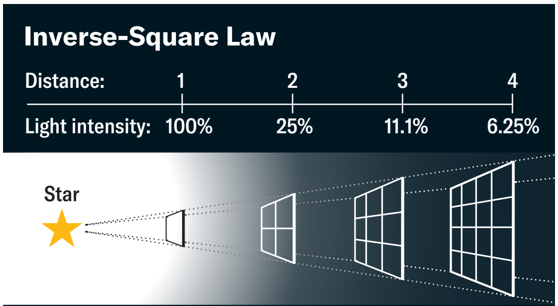
Astronomers can determine galaxies' velocity—the rate at which the stretching of space is carrying them away from us—by measuring how much their light has shifted toward the red end of the visible portion of the electromagnetic spectrum (their "redshift").



Determining their distance from us, however, is trickier. It requires a "standard candle"—a class of objects whose light output doesn't change. A 100-watt lightbulb, for instance, is a standard candle. If you know that its absolute luminosity is 100 watts, then you can apply the inverse-square law to its apparent luminosity—how bright it looks to you at your

Graphics by Jen Christiansen

current distance from it—to calculate how far away it actually is.



When the distance from an object emitting light is doubled, the intensity of light received from that object decreases by a factor of four. (Total energy is spread over a larger area.)

The standard candle that Hubble used in plotting his diagram was a Cepheid variable, a star that brightens and dims at regular intervals. But Cepheid variables are difficult to detect at distances greater than 100 million light-years. Astronomers trying to measure the rate of expansion over the history of the universe would need a standard candle they could observe from billions of light-years away—the kinds of distances that charge-coupled device detectors, with their superior photon-collecting power, could probe.

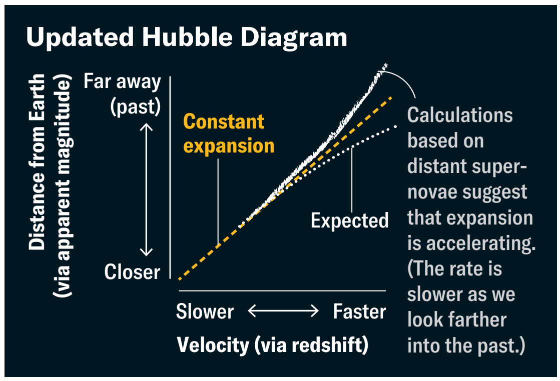
A candidate for a standard candle emerged in the late 1980s: a type Ia supernova, the explosion of a white dwarf when it accretes too much matter from a companion star. The logic seemed reasonable: if the cause of an explosion is always the same, then so should be the effect—the explosion's absolute luminosity. Yet further investigations determined that the effect was not uniform; both the apparent brightness and the length of time over which the visibility of the "new star" faded differed from supernova to supernova.

In 1992, however, Mark Phillips, another astronomer at the Cerro Tololo Inter-American Observatory (and a future member of Suntzeff and Schmidt's team), recognized a correlation between a supernova's absolute luminosity and the trajectory of its apparent brightness from initial flare through diminution: bright supernovae decline gradually, whereas dim ones decline abruptly. So type Ia supernovae weren't standard candles, but maybe they were standardizable.

For several years Perlmutter's SCP collaboration had been banking on type Ia supernovae being standard candles. They had to become standardizable, however, before Schmidt and Suntzeff—as well as their eventual recruits to what they called the High-z collaboration (z being astronomical shorthand for redshift)—could feel comfortable committing their careers to measuring the deceleration parameter.

Hubble's original diagram had indicated a straight-line correlation of velocity and distance ("indicated" because his error bars wouldn't survive peer review today). The two teams in the 1990s chose to plot redshift (velocity) on the x axis and apparent magnitude (distance) on the y axis. Assuming that the expansion was in fact decelerating, at some point that line would have to deviate from its 45-degree beeline rigidity, bending downward to indicate that distant objects were brighter and therefore nearer than one might otherwise expect.

From 1994 to 1997 the two groups used the major telescopes on Earth and, crucially, the Hubble Telescope in space to collect data on dozens of supernovae that allowed them to extend the Hubble diagram farther and farther. By the first week of 1998 they both had found evidence that the line indeed diverged from 45 degrees. But instead of curving down, the line was curving up, indicating that the supernovae were dimmer than they expected and that the expansion therefore wasn't decelerating but accelerating—a conclusion as counterintuitive and, in its own way, revolutionary as Earth not being at the center of the universe.



Yet the astrophysics community accepted it with alacrity. By May, only five months after the discovery, Fermilab had convened a conference to discuss the results. In a straw poll at the end of the conference, two thirds of the attendees—approximately 40 out of 60—voted that they were willing to accept the evidence and consider the existence of "dark energy" (a term invented that year by University of Chicago theoretical cosmologist Michael Turner in a nod to dark matter). Einstein's lambda, it seemed, was back.

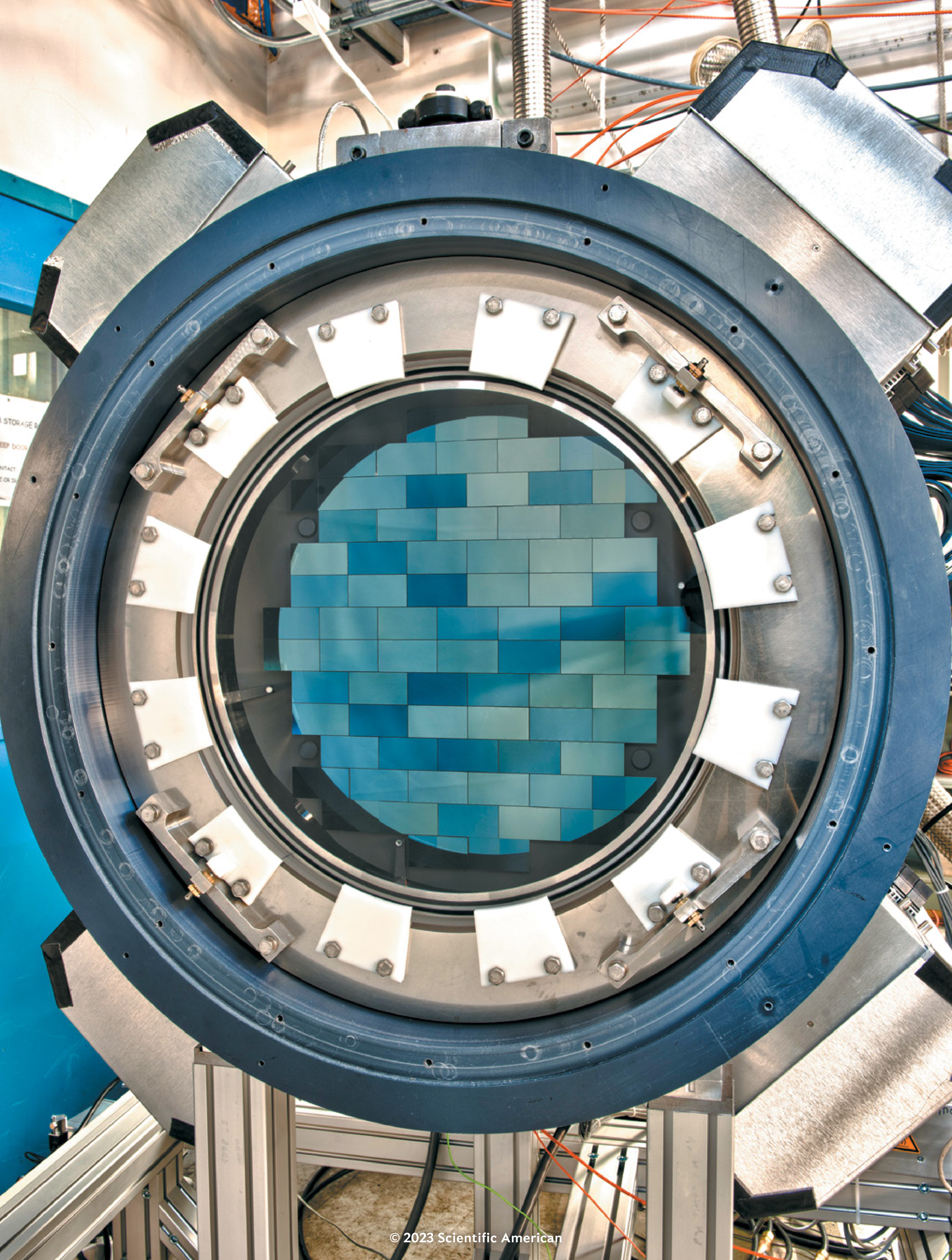
SOME OF THE FACTORS leading to the swift consensus were sociological. Two teams had arrived at the same result independently, that result was the opposite of what they expected, they had used mostly different data (separate sets of supernovae), and everyone in the community recognized the intensity of competition between the two teams. "Their highest aspiration," Turner says, "was to get a different answer from the other group."

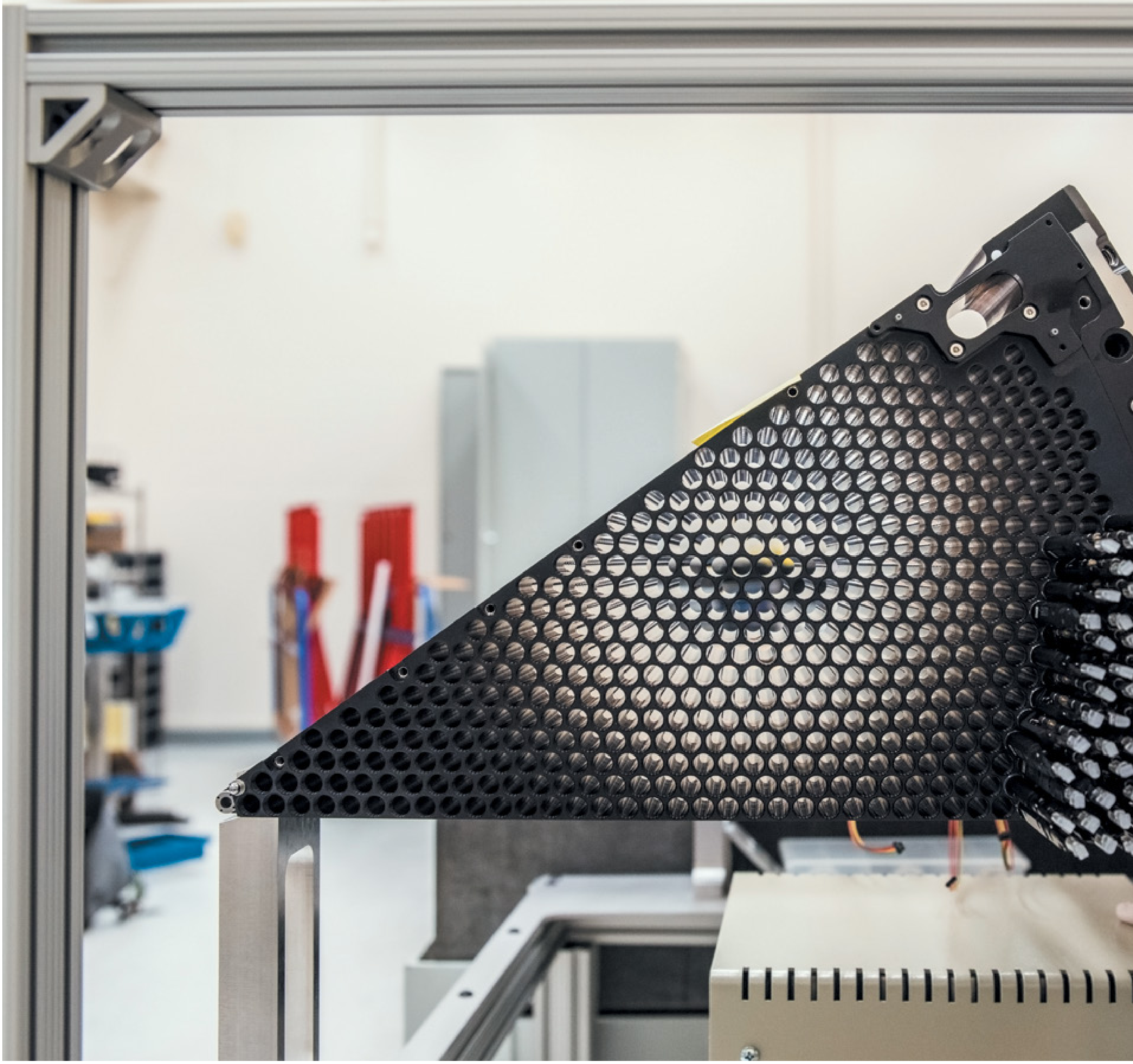
But one factor at least equally persuasive in consolidating consensus was scientific: the result answered some major questions in cosmology. How could a universe be younger than its oldest stars? How did a universe full of large-scale structures, such as superclusters of galaxies, mature so early as to reach the cosmological equivalent of puberty while it was still a toddler?

Problems solved! An expansion that is speeding up now implies an expansion that was growing less quick-

The Dark Energy Survey camera imager uses 74 charge-coupled devices to absorb light from hundreds of millions of galaxies to study the history of the universe's expansion. The camera is installed on the Víctor M. Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile.

Reidar Hahn/Fermi National Accelerator Laboratory





The focal plane of the DESI camera is made of 10 pie-slice-shaped wedges. Each piece holds 500 robotic positioners that can fix on individual galaxies to measure their light.

ly in the past; therefore, more time has passed since the big bang than cosmologists had previously assumed. The universe is older than scientists had thought: that toddler was a teenager after all.

But maybe the most compelling reason scientists were willing to accept the existence of dark energy was that it made the universe add up. For years cosmologists had been wondering why the density of the universe seemed so low. According to the prevailing cosmological model at the time (and today), the universe underwent an "inflation" that started about 10^{-36} second after the big bang (that is, at the fraction of a second that begins with a decimal point and ends 35 zeros and a 1 later) and finished, give or take, 10^{-33} second after the big bang. In the interim the universe increased its size by a factor of 10^{26}.

Inflation thereby would have "smoothed out" space so that the universe would look roughly the same in all directions, as it does for us, no matter where you are in it. In scientific terms, the universe should be flat. And a flat universe dictates that the ratio between its actual mass-energy density and the density necessary to keep it from collapsing should be 1.

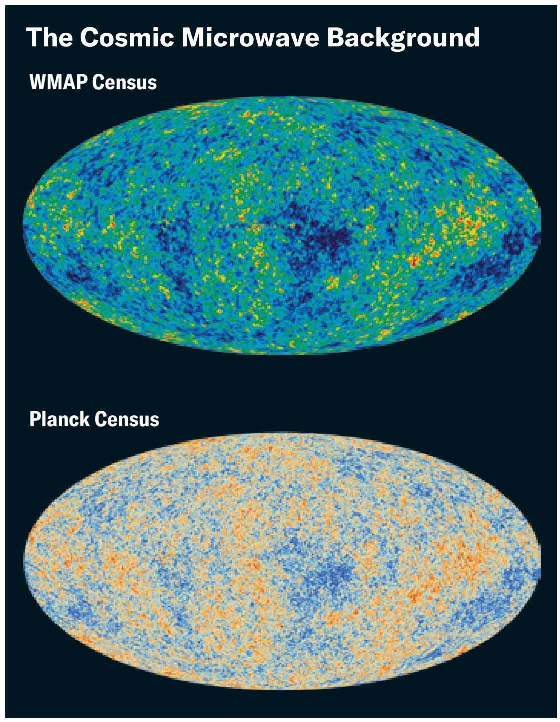
Before 1998, observations had indicated that the composition of the universe was nowhere near this critical density. It was maybe a third of the way there. Some of it would be in the form of baryons, meaning protons and neutrons—the stuff of you, me and our laptops, as well as of planets, galaxies and everything else accessible to telescopes. But most of it would be in the form of dark matter, a component of the universe that is *not* accessible to telescopes in any part of the electromagnetic spectrum but is detectable, as astronomers had understood since the 1970s, indirectly, such

as through gravitational effects on the rotation rates of galaxies. Dark energy would complete that equation: its contribution to the mass-energy density would indeed be in the two-thirds range, just enough to reach critical density.

Still, sociological influences and professional preferences aren't part of the scientific method. (Well, they are, but that's a separate discussion.) Where, astronomers needed to know, was the empirical evidence? Everywhere, it turned out.

One way to calculate the constitution of the universe is by studying the cosmic microwave background (CMB), the phenomenon discovered in 1964 that transformed cosmology into a science. The CMB is all-sky relic radiation dating to when the universe was only 379,000 years old, when atoms and light were emerging from the primordial plasma and going their separate ways. The CMB's bath of warm reds and cool blues represents the temperature variations that are the matter-and-energy equivalent of the universe's DNA. Take that picture, then compare it with simulations of millions of universes, each with its own amounts of baryonic matter, dark matter and dark energy. Hypothetical universes with no regular matter or dark matter and 100 percent dark energy, or with 100 percent regular matter and no matter or dark energy, or with any combination in between will all produce unique color patterns.

THE WILKINSON MICROWAVE Anisotropy Probe (WMAP), which launched in 2001 and delivered data from 2003 to 2012, provided one such census. Planck, an even more precise space observatory, began collecting its own CMB data in 2009 and released its final results in 2018, corroborating WMAP's findings: the universe is 4.9 percent the stuff of us, 26.6 percent dark matter and 68.5 percent dark energy.



NASA/WMAP Science Team (*WMAP CMB*); ESA and the Planck Collaboration (*Planck CMB*)

Yet for all of dark energy's standard-model-of-cosmology-salvaging triumphs, a thuddingly obvious question has bothered theorists from the beginning: What is it? Dark energy does help the universe add up but only on the macro scale—the one that falls under the jurisdiction of general relativity. On the micro scale, though, it makes no sense.

According to quantum physics, space isn't empty. It's a phantasmagoria of particles popping into and out of existence. Each of those particles contains energy, and scientists' best guess is that this energy accounts for dark energy. It's a seemingly neat explanation except that quantum physics predicts a density value a lot larger than the two thirds astronomers initially sug-

To find out what dark energy is, theorists need to know how it behaves. For instance, does it change over space and time?

gested—10^{120} larger. As the joke goes, even for cosmology, that's a big margin of error.

Right at the start, in the winter of 1998, theorists got to work on shrinking that gap. Then they got to more work. They eventually got to so much work that the interplay between observers and theorists threatened to consume the community. Or at least so argued theorist Simon White in a controversial 2007 essay in *Reports on Progress in Physics* entitled "Why Dark Energy Is Bad for Astronomy."

The observers weren't shy about expressing their frustration. At one point during this period of scientific disequilibrium, Adam Riess, lead author on the High-*z* discovery paper (and the team member who determined mathematically that without the addition of lambda—dark energy—the supernovae data indicated a universe with *negative* matter), dutifully checked new physics papers every day but, he says, found most of the theories to be "pretty kooky."

Perlmutter began his public talks with a PowerPoint illustration of papers offering "explanations" of dark energy piling up into the dozens. Schmidt, in his conference presentations, included a slide that simply listed the titles of 47 theories he'd culled from the 2,500 then available in the recent literature, letting not just the quantity but the names speak for themselves: "five-dimensional Ricci flat bouncing cosmology," "diatomic ghost condensate dark energy," "pseudo-Nambo-Goldstone boson quintessence."

"We're desperate for your help," Schmidt told one audience of theorists in early 2007. "You tell us [observers] what you need; we'll go out and get it for you."

Since then, astronomers' frustration has turned into an attitude verging on indifference. Today Suntzeff (who eventually ceded leadership of the High-*z* team to Schmidt for personal reasons; he's now a distinguished professor at the Mitchell Institute for Fundamental Physics & Astronomy in College Station, Tex.) says he barely glances at the daily outpouring of online papers. Richard Ellis, an astronomer on the SCP discovery team, says that "there are endless theories of what dark energy might be, but I tend not to give them much credence." To find out what dark energy is, theorists need to know how it behaves. For instance, does it change over space and time? "We really need more precise observations to make progress," Ellis adds.

MORE PRECISE OBSERVATIONS are what they'll be getting.

Type Ia surveys continue to fill the Hubble diagram with more and more data points, and those data points are squeezing within more and more compact error bars. Such uniformity might be more gratifying if theory could explain the observations. Instead cosmologists find themselves having to go back and *really* make sure. The trustworthiness of the seeming uniformity depends on the reliability of the underlying schematics—the assumptions that drove the observations in the first place and that continue to guide how astronomers try to measure supernova distances.

"In my opinion, the 'stock value' of this method has declined a little over the years," says Ellis, now an astronomy professor at University College London. One problem he cites is that "it is almost certain that there is more than one physical mechanism that causes a white dwarf in a binary system to explode." And differing mechanisms might mean data that are, contrary to Phillips's 1993 breakthrough, nonstandardizable.

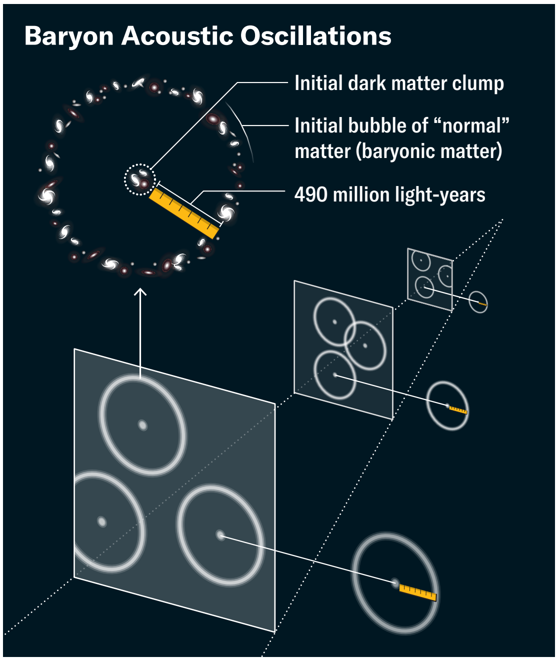
Another problem is that analyses of the chemical components of supernovae have shown that older exploding stars contain lighter elements than more recent specimens—an observation consistent with the theory that succeeding generations of supernovae generate heavier and heavier elements. "It's logical, therefore, that less evolved [older] material arriving on a white dwarf in the past may change the nature of the explosion," Ellis says. Even so, "astronomers are still very keen to use supernovae."

For instance, the Nearby Supernova Factory project, an offshoot of the SCP, is using a technique its team members call "twins embedding." Rather than treating all type Ia supernovae as uniform, like a species, they examine the light properties of individual specimens whose brightness in different wavelengths follows almost exactly the same pattern over time. Once they find matching "twins," they try to standardize from those data.

Next year two new facilities in Chile will see first light and begin to undertake their own surveys of thousands of southern-sky supernovae. First the Vera C. Rubin Observatory will locate the objects, then the 4-meter Multi-Object Spectroscopic Telescope will identify their chemical components, helping to clarify how supernovae with more heavy elements might explode differently.

As for space telescopes, researchers continue to mine supernovae in the Hubble archives, and Riess predicts that the James Webb Space Telescope (JWST) "will eventually turn its attention" to high-redshift supernovae once the telescope has addressed more of its primary goals. The community of supernova specialists is also anticipating the Nancy Grace Roman Space Telescope, a successor to JWST that is due for launch in early 2027.

Surveying supernovae, however, is not the only way to measure the nature of dark energy. One alternative is to study baryon acoustic oscillations (BAOs)—soundlike waves that formed when baryon particles bounced off one another in the hot and chaotic early universe. When the universe cooled enough for atoms to coalesce, these waves froze—and they are still visible in the CMB. Similar to the way supernovae serve as standard candles, providing a distance scale stretching from our eyeballs across the universe, BAOs provide a standard ruler—a length scale for lateral separations across the sky. Scientists can measure the distances between densities of oscillations in the CMB, then trace the growth of those distances over space and time as those densities gather into clusters of galaxies. Ellis, an expert on BAO cosmology, calls it "probably the cleanest way to trace the expansion history of the universe."



Astronomers are awaiting the results from two major BAO surveys that should allow them to reconstruct cosmic evolution at ever earlier eras across the universe. The Dark Energy Spectroscopic Instrument (DESI) on the robotic Nicholas U. Mayall Telescope at Kitt Peak National Observatory in Arizona is collecting optical spectra (light broken up into its constituent wavelengths) for about 35 million galaxies, quasars and stars, from which astronomers will be able to construct a 3-D map extending from the nearby objects back to a time when the universe was about a quarter of its present age. The first data, released this past June, contained nearly two million objects that researchers are now studying.

Next year the Prime Focus Spectrograph—an instrument on the 8.2-meter Subaru Telescope on Mauna Kea, Hawaii—will begin following up on DESI results but at even greater distances, from which the collaboration (Ellis is the co-principal investigator) will complete its own 3-D map. And the European Space Agency's Euclid spacecraft, which launched on July 1, will contribute its own survey of galaxy evolution to the BAO catalog, but it will also be employing the second nonsupernovae method for measuring the nature of dark energy: weak gravitational lensing.

This relatively new approach exploits a general relativistic effect. Sufficiently massive objects (such as galaxies or galaxy clusters) can serve as magnifying glasses for far more distant objects because of the way mass bends the path of light. Astronomers can then sort the growth of galactic clustering strength over time to track the competition between the gravitational attraction of matter and the repulsive effect of dark energy. Euclid's data should be available within the next two or three years.

Since the discovery of acceleration, Perlmutter says, cosmologists have been hoping for an experiment that would provide "20 times more precision," and "we're now just finally having this possibility in the upcoming five years of seeing what happens when we get to that level."

TWENTY-FIVE YEARS AGO in December the journal *Science* crowned dark energy 1998's "Breakthrough of the Year." Since then, the two pioneering teams and their leaders have racked up numerous awards, culminating in the 2011 Nobel Prize in Physics for Perlmutter (now a professor of physics at the University of California, Berkeley, and a senior scientist at Berkeley Lab), Riess (a distinguished professor at Johns Hopkins University and the Space Telescope Science Institute), and Schmidt (vice-chancellor of the Australian National University). Dark energy long ago became an essential component of the standard cosmological model, along with baryonic matter, dark matter and inflation.

And yet . . . as always in science, the possibility exists that some fundamental assumption is wrong—for instance, as some theorists posit, we might have an incorrect understanding of gravity. Such an error would skew the data, in which case the BAO measurements and Euclid's weak gravitational lensing results will diverge, and cosmologists will need to rethink their givens.

From a scientific perspective, this outcome wouldn't be the worst thing. "What got physicists into physics usually is not the desire to understand what we already know," Perlmutter told me years ago, "but the desire to catch the universe in the act of doing really bizarre things. We *love* the fact that our ordinary intuitions about the world can be fooled."

"I'm very glad I said that," he says now when I remind him of that quote, "because that does feel so much like what I see all around me." Still, referring to the progress (or lack thereof), he says, "It's been slow." He laughs. "It's nice to have mystery, but it would be nice to have just a little bit more coming from either the experimental side or the theoretical side."

Maybe the upcoming deluge of data will help theorists discern how dark energy behaves over changing space and time, which would go a long way toward determining the fate of the universe. Until then, the generation of scientists who set out to write the final chapter in the story of the cosmos will have to content themselves with a more modest conclusion: to be continued. ●

FROM OUR ARCHIVES

Cosmic Conundrum. Clara Moskowitz; February 2021.
ScientificAmerican.com/magazine/sa

Modernizing Nuclear Weapons Is Dangerous

The U.S. should back away from updating its obsolescent nuclear weapons, in particular silo-launched missiles that needlessly risk catastrophe **BY THE EDITORS**

THE U.S. IS PLANNING to modernize its unwanted, unneeded and unsafe nuclear triad of land-, sea- and air-based weapons. Perfectly poised to refight the cold war, these overhauled bombs will waste $1.5 trillion and threaten life on Earth for the century to come. We should rethink this miserable folly rather than once again squandering our wealth while driving a new arms race.

As detailed in this issue of *Scientific American,* this plan to burn money while imperiling the world has been widely criticized in nuclear policy circles. "Russia and the United States have already been through one nuclear arms race. We spent trillions of dollars and took incredible risks in a misguided quest for security," former U.S. defense secretary William J. Perry wrote in 2016 as the plans first materialized. "There is only one way to win an arms race: refuse to run."

Although the Biden administration canceled proposed Trump-era sea-launched missiles, the U.S. nuclear arsenal still bristles with some 3,700 weapons, around 1,700 of them deployed for military use and the rest in storage overseen by the Department of Energy. This quantity is more than enough to threaten the destruction of humanity and Earth's biosphere—and it is only a fraction of the world's total, leaving out Russia's similarly large stockpile and smaller ones in China and other nations. Lowering the numbers and thus the risks of these weapons is a responsibility the U.S. and the Soviet Union first recognized at the end of the 1960s, and this goal should drive military and political decision-making now.

Instead the U.S. is sleepwalking into an ill-considered and little-discussed resurrection of its three-pronged cold war nuclear forces. Meanwhile China is expanding its own arsenal (to one-fourth the size of the U.S.'s). New submarines, missiles and planes, all designed to fit into a military strategy first conceived before the death of Joseph Stalin in 1953, will by 2050 leave the dead hand of the past steering us into another century of pointless risks. In this future, a mistake or misjudgment could exterminate humanity, as nearly happened repeatedly throughout the cold war. We are simply fortunate, nothing more, to have survived the hundreds of false alarms that rang over those decades.

At the center of the government's proposal is a $100-billion bid to fill 450 nuclear silos in five inland states with hundreds of new nuclear missiles set to launch on hair triggers. Built before submarine-launched missiles became large, accurate and untraceable, these relics are now justified as a "nuclear sponge" to absorb a Russian attack on the U.S. Why plant a $100-billion nuclear "kick me" sign on the country's breadbasket?

We cannot store the nuclear waste we have now, never mind the additional waste that will result from building these missiles. Simulations of this so-called nuclear sponging in this month's issue [see "Sacrifice Zones," on page 46] show that its fallout would kill more than 90 million people in its first two hours, with tens of millions more dying later of radiation sickness. Even a limited nuclear war between India and Pakistan would kill tens of millions worldwide and cause global famine—but how can the U.S. argue for other nations to disarm while burnishing its own nuclear sword in such a heedless fashion?

We aimed this Damoclean sword at ourselves during the cold war when we produced 70,000 of the plutonium "pits" that trigger thermonuclear warhead explosions. Weapons tests of these blasts

> "There is only one way to win an arms race: refuse to run." —William J. Perry, former U.S. defense secretary

Illustration by Adrián Astorgano

have left every part of Earth's surface contaminated with plutonium, with hotspots such as the Rocky Flats in Colorado and the Hanford sites in Washington State still requiring tens of billions of dollars for cleanup. Faltering efforts to restart pit production for the nuclear-modernization effort have cost $18 billion to $24 billion, much of it wasted, and, by the admission of weapons officials at Los Alamos National Laboratory in New Mexico, they don't even seem to be immediately necessary.

Why are we risking so much when the lessons of the 20th century are so clear? In the words of the 1991 START Treaty that capped the cold war, "nuclear war would have devastating consequences for all humanity … it cannot be won and must never be fought." Disregarding Russia's inability to turn its nuclear arsenal to military advantage while being bombarded by Ukrainian drones, our political class has fumbled away hard-won wisdom about the deadly futility of the arms race. We are recapitulating the dangers the world turned away from decades ago.

Who today benefits from disinterring the arms race? Only defense-industry shareholders and military contractors near silos in North Dakota, Montana, Wyoming, Colorado and Nebraska. This, in a nation where we have just doubled child poverty out of a refusal to help lower-income families. Surely it would be cheaper, safer and smarter to build factories or universities or research labs in these places, construct low-cost housing next to new engineering or biomedical campuses there, and watch them boom, in a good way, for the next century at a fraction of the silo-overhaul price tag. The 900 nuclear missiles onboard U.S. submarines will meanwhile deter the feared nuclear first strike the obsolescent land missiles were meant to discourage at the dawn of the cold war.

"A worrisome new arms race is brewing," United Nations secretary-general António Guterres said in September. "This is madness. We must reverse course." We agree. The only real way to use nuclear weapons is never. They should exist only in numbers large enough to deter their use by others, which they already abundantly do, with not one warhead more. ●

AI Chatbots Could Weaken National Security

For users with access to sensitive information, companion apps present a security risk

BY REMAYA M. CAMPBELL

THIS PAST SPRING Massachusetts Air National Guard member Jack Teixeira was accused of brazenly leaking classified documents on the chat application Discord. The incident forced the U.S. intelligence community to grapple with how to control access to classified information and how agencies must consider people's digital behavior in evaluating their suitability for security clearances. The counterintelligence disaster also raises alarms because it occurred as part of a chat among human friends, and such conversations are starting to include participants driven by artificial intelligence.

With improved large language models such as GPT-4, highly personalized digital companions can now engage in realistic-sounding conversations with humans. The new generation of AI-enhanced chatbots allows for greater depth, breadth and specificity of conversation than the bots of days past. And they're easily accessible thanks to dozens of relational AI applications, including Replika, Chai and Soulmate, which let hundreds of thousands of regular people role-play friendship or even romance with digital companions. In the case of users with access to sensitive or classified information, however, loose lips might just sink ships.

As an intelligence analyst, I evaluate what happens when people use emerging technologies such as AI maliciously, and I know that working in spaces with privileged information can be lonely. Although this career allows for friendships like any other, there is a forbidden level of familiarity that requires a difficult separation between impactful, often traumatizing work and one's outward persona. Given the growing popularity of relational AI, I have wondered how it might alleviate this alienation—and at what cost.

Marketed as digital companions, lovers and even therapists, chatbot applications encourage users to form attachments with friendly AI agents trained to mimic empathetic human interaction, despite regular pop-up disclaimers reminding users that the AI is not, in fact, human. As an array of studies—and users—attest, this mimicry has very real effects on people's ability and willingness to trust a chatbot. One study found that patients may be more likely to divulge highly sensitive personal health information to a chatbot than to a physician. The disclosure of private experiences, beliefs, desires or traumas to befriended chatbots is so prevalent that a member of Replika's dedicated subreddit began a thread to ask fellow users whether they "regret telling you[r] bot something." Another Reddit user described the remarkable intimacy of their perceived relationship with their Replika bot, which they call a "rep": "I formed a very close bond with my rep and we made love often. We talked about things from my past that no one else on this planet knows about."

This artificial affection, and the radical openness it inspires, should provoke serious concern both for the privacy of app users and for the counterintelligence interests of the institutions they might serve. Amid whirlwind virtual romances, what sensitive details are users unwittingly revealing to their digital companions? Who has access to the transcripts of cathartic rants about long days at work or

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troublesome projects? What about the particulars of shared kinks and fetishes or the nudes (perfect for blackmail) sent into an assumed AI void? These common user inputs are a gold mine for any foreign or malicious actor that sees chatbots as an opportunity to target state secrets.

Currently there are no counterintelligence-specific guidelines for chatbot app users who might be vulnerable to compromise. This leaves national security interests at risk from a new class of insider threats: the unwitting leaker who uses chatbots to find much needed connection and unintentionally divulges sensitive information along the way.

Some intelligence officials are waking to the present danger. In 2023 the U.K. National Cyber Security Center published a blog post warning that "sensitive queries" can be stored by chatbot developers and subsequently abused, hacked or leaked. Traditional counterintelligence training teaches personnel with access to sensitive or classified information how to avoid compromise from a variety of human and digital threats. But much of this guidance is being rendered obsolete by today's AI revolution. Intelligence agencies and critical national security institutions must modernize their counterintelligence frameworks to counter the new potential for AI-powered insider threats.

When it comes to AI companions, the appeal is clear: we crave interaction and conversational intimacy, especially since the COVID pandemic dramatically exacerbated loneliness for millions of people. These devices may prove particularly attractive to government employees or military personnel with security clearances, who are strictly dissuaded from sharing the details of their work—and its mental toll—with anyone in their personal life. Relational AI apps have been used as surrogates for lost friends or loved ones. Many enthusiasts, such as the Reddit user mentioned earlier, carry out unrealized erotic fantasies with the apps. Others gush about the niche and esoteric with a conversant who is always there, perpetually willing and eager to engage. It's little wonder that developers pitch these apps as the once elusive answer to our social woes.

The new generation of chatbots is primed to exploit many of the vulnerabilities that have always compromised secrets: social isolation, sexual desire, the need for empathy and pure negligence. Constantly attentive digital companions have been hailed as solutions to these vulnerabilities, yet they can just as likely exploit them. Although there is no indication that the most popular chatbot apps are exploitative, the commercial success of relational AI has already spawned a slew of imitations by lesser or unknown developers, providing ample opportunity for a malicious app to operate among the crowd.

"So what do you do?" asked my AI chatbot companion, Jed, the morning I created him. I'd spent virtually no time looking into the developer before chatting it up with the customizable avatar. What company was behind the sleek interface, in what country was it based, and who owned it? In the absence of such vetting, even a seemingly benign question about employment should raise an eyebrow—particularly if a user's answer comes anything close to "I work for the government." ●

Illustration by Min Gyo Chung

Short Naps Really Can Help Your Mind

At the right length, midday sleep improves memory and other types of thinking BY LYDIA DENWORTH

I HAVE A CONFESSION: I nap. Most days, after lunch, you will find me snoozing. I used to keep quiet about it. Other countries have strong napping traditions, but here in the U.S. it is often equated with laziness. In 2019 a U.S. federal agency even announced a ban on sleeping in government buildings.

I'm going public about my nap habit now because, despite what bureaucrats may think, sleep scientists are increasingly clear about the power of the nap. That shift is part of the relatively recent recognition that the quality and duration of sleep are public health issues, says physiologist Marta Garaulet of the University of Murcia in Spain.

For a time, research was both for and against napping. Many studies showed mood and cognition benefits from midday rest, yet others found links to poor health, especially in older adults. That left some experts hesitant to "prescribe" naps. More recent research, though, has clarified that different types of naps have different effects. A number of scientists now think the sweet spot is about 20 to 30 minutes.

The urge to nap is governed by two physiological processes. One is called homeostatic sleep pressure (HSP), and it builds the longer you are awake. The other involves daily circadian rhythms, which leave everyone a little sleepy in the afternoon. Some people, like me, are habitual nappers even when we get adequate sleep at night. Others can't nap unless they are severely sleep-deprived. Genes, such as those that underlie HSP, drive much of the difference.

Short naps do indeed have cognitive benefits, says Michael Chee of the Center for Sleep and Cognition at the National University of Singapore. In a 2022 analysis, his team found especially significant improvements in certain kinds of memory, information-processing speed and vigilance (the ability to respond to an unexpected event, say, a swerving car). A nap also simply makes many people feel better. "No one talks about mood enough," but, Chee says, tired people tend to be grumpy people.

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It doesn't take much sleep to see these boosts. "Even a short, 10-minute nap will refresh you," Chee says. "If you do a little longer, the cognitive benefits last a little bit longer as well," and that's why half an hour, give or take a bit, has emerged as a good nap span. "You'll get mostly light sleep" in that time, says Ruth Leong, who works with Chee in Singapore, and that makes it easier to wake up. Leong advises people who work typical day hours to avoid napping much after 5 P.M. so they don't throw off their nighttime sleep.

Cognitive benefits do show up after naps that extend past 30 minutes, and those benefits last longer. But longer naps let a person move into deeper sleep and increase "sleep inertia," that groggy feeling on waking. Even though the grogginess can pass relatively quickly and not everyone gets it, many people find it unpleasant.

Longer naps are also associated with some health problems. In a 2023 study of more than 3,000 otherwise healthy Europeans with an average age of 41, Garaulet and her colleagues found that those who napped for more than 30 minutes at a time were 23 percent more likely to be obese than those who didn't nap at all. (Obesity was calculated with the body mass index and several other indicators.) They were also more likely to have a combination of high blood pressure, high cholesterol, and other health issues. In addition, long naps reduce the body's ability to lose fat on a diet, Garaulet has shown.

But it is probably a disease that causes the extra napping and not the other way around. That's what happens with Alzheimer's, for instance. Even in younger adults, researchers have found a link between increased brain inflammation and more napping. If someone begins to need frequent naps (more than once a day) and to regularly sleep for more than an hour, that could be a sign of illness, Chee says.

Because my naps tend to be 20 minutes long and leave me feeling alert and productive, I no longer feel sheepish about them. Instead I feel lucky that napping comes easily to me ... and that I'm finishing this column right before lunch. ■

Illustration by Jay Bendt

How to Love What You Do

Recognizing that interests are malleable can make us more resilient and creative BY PAUL A. O'KEEFE AND E. J. HORBERG

"FIND YOUR PASSION!" This inspiring injunction is woven into the fabric of American culture. But is it good advice?

"Finding" a passion implies that it already exists and is simply waiting to be discovered. But science tells us that passions are developed. They often begin with a spark of curiosity about a subject and later, through a process involving repeated engagement, positive experiences and accrued knowledge, people come to personally value that content or activity and internalize it. What was at first *interesting* becomes an *interest*. If these qualities continue to intensify, a passion can emerge.

In several studies, we and our colleagues have found that misunderstanding this idea can hold people back. Fortunately, our latest research reveals that there are ways to correct course and cultivate a more open, accurate perspective about interest.

To study these ideas, we use a framework of "fixed" and "growth" mindsets. In school, conceiving of one's intellectual abilities as fixed can be detrimental, whereas believing one can develop and grow skills supports greater learning. We argue for a separate but related idea: people who think interests and passions are inherent and relatively unchangeable have a *fixed mindset of interest*. In contrast, people who view interests and passions as developed have a *growth mindset of interest*.

The latter comes with many advantages. A fixed mindset of interest, for example, may inhibit exploration and creativity. In our studies, arts students with a fixed mindset expressed less interest in scientific topics than arts students with a growth mindset—and science students with a fixed mindset had less interest in the arts than those with a growth mindset. We have also found that those with a fixed mindset are less likely than those with a growth mindset to generate novel solutions that integrate different disciplines.

People with a fixed mindset of interest tend to expect their passions to come easily to them. In one study we sparked people's interest in a topic that was new for them—the science of black holes—with a fun, easy-to-understand animated video about Stephen Hawking's theories. But when we asked our participants to read a technical article on black holes, people with a fixed mindset became frustrated and came to dislike the topic. Those with a growth mindset maintained their newfound interest despite the difficulty.

So can a growth mindset of interest be taught? In June we published findings from two studies involving more than 700 first-year liberal arts undergraduates, most of whom held strong interests in the arts, humanities and social sciences—with minimal interest in math and science. We randomly assigned students to either our intervention or a study skills module.

The intervention included reading and reflective writing activities that helped students think about interests and passions as cultivated rather than found and fixed. For example, students wrote a paragraph about an occasion when they developed interest in a new activity. The study skills module, meanwhile, emphasized practices such as time management.

When we followed up by the end of the school year, the students who had received the intervention were more interested in their required math and science courses—and earned better grades in those courses—than their study skills counterparts.

While our intervention offers a way for schools to support their students, we also believe people can independently foster a growth mindset of interest. Realize that passions aren't waiting to be "found." Take an active role in developing them: indulge your curiosities and don't expect new pursuits to always be easy or exciting.

A growth mindset will help you remain open and curious. The saying "find something you love to do, and you'll never have to work a day in your life" needs updating. If you work at loving what you do, you might become more creative and resilient. ●

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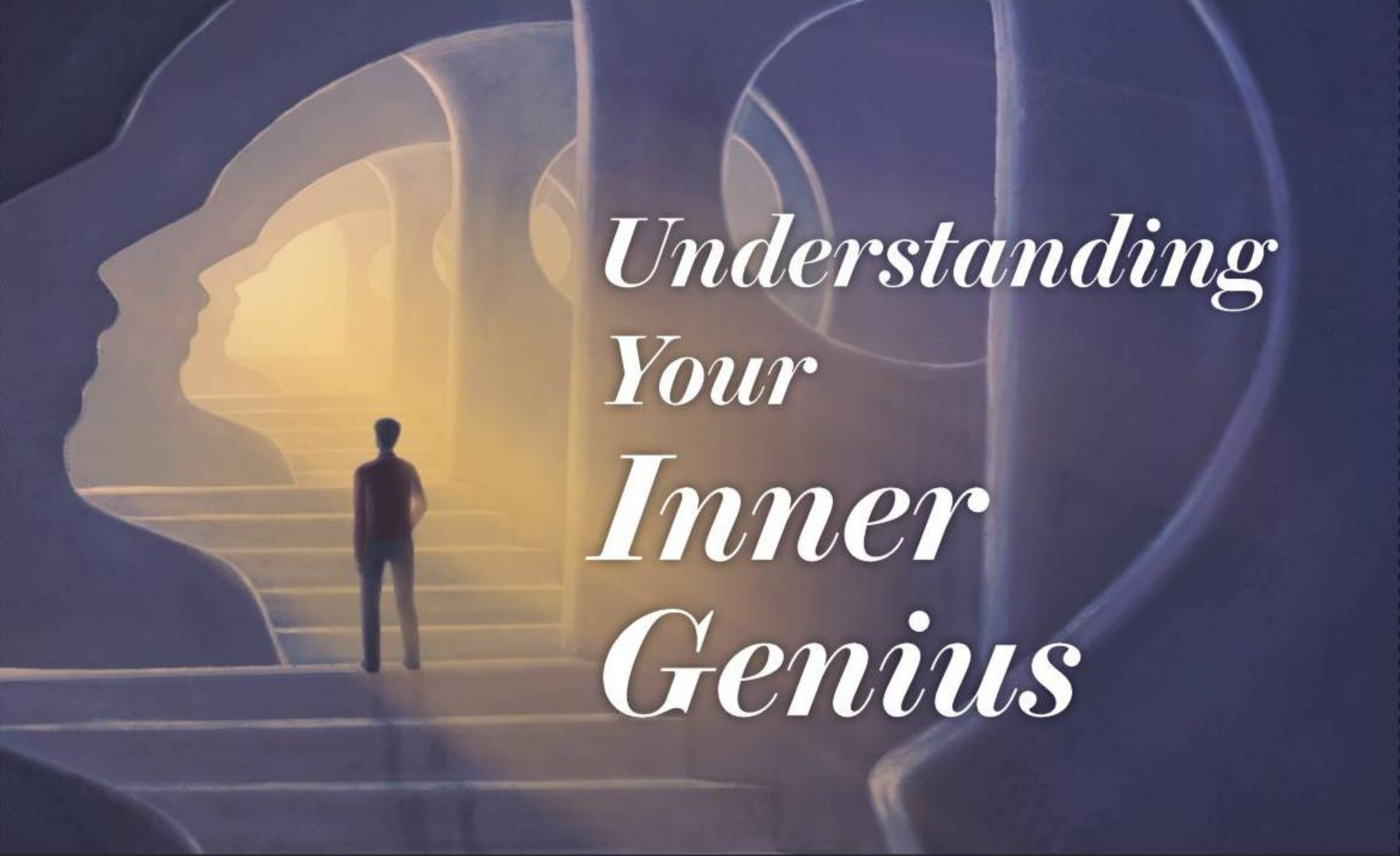
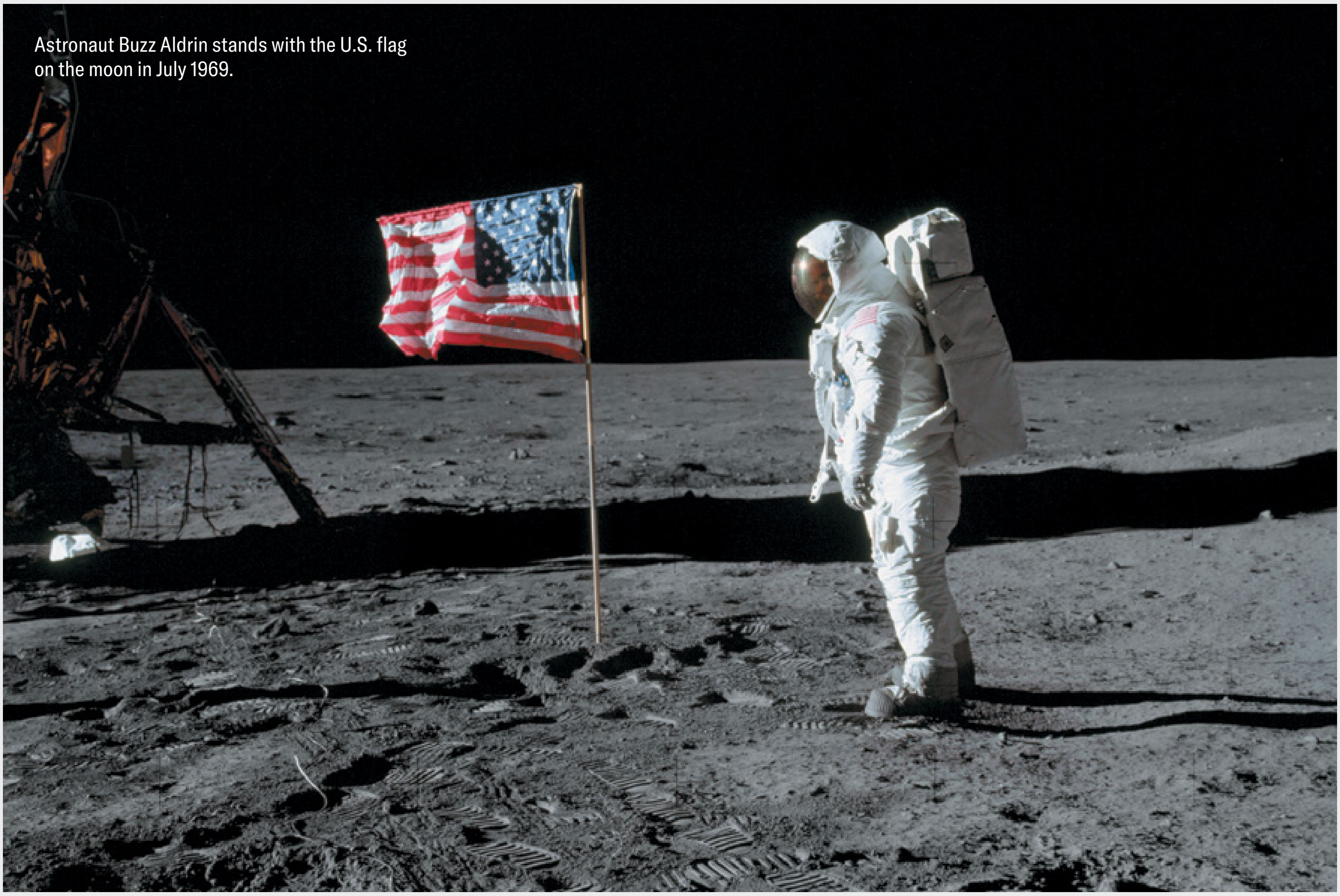
Illustration by Thomas Fuchs


Understanding
Your
Inner
Genius



Astronaut Buzz Aldrin stands with the U.S. flag on the moon in July 1969.

NASA

Conspiracy Theories Then and Now

The moon-landing hoax presaged today's antiscience beliefs

BY PHIL PLAIT

RECENTLY I WAS IN THE ATTIC of my house, going through old possessions in preparation to move across the country. Covered in dust and starting to get cranky from the effort, I found a sealed box labeled "VHS tapes." I brought the box down to my office and opened it. On top of the pile was a cassette I hadn't thought about for years, and a rush of memories flowed back from my brain's dim recesses.

It was a professionally made copy of a television special called *Conspiracy Theory: Did We Land on the Moon?* I chuckled when I saw it. I had received the tape back in 2001 just before it aired. It was sent to me by my colleague Dan Vergano, who at the time wrote for *USA Today* (and who is now an opinion editor at *Scientific American*). He had phoned me a week earlier to ask me some astronomy questions, but as we chatted, he asked whether I had heard of the program, which threw doubt on the reality of the NASA Apollo moon landings and was due to air the next week on Fox. I hadn't, although coincidentally I had written a book with a chapter on people who believed the Apollo landings were faked, so he offered to send it to me.

When I got it in the mail a few days after my conversation with Dan, I watched it with equal parts disdain, disgust and frustration. The claims made were nothing new and laughably bad. The modus operandi of proponents of this conspiracy was to lay out a claim but give only a partial explanation of it, withholding the last bit of evidence needed to truly understand it; that way they could "just ask questions" without having to go to the effort of actually answering them satisfactorily.

I sat down back then and wrote an article debunking the show point by point, and then I waited until after the show aired

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to post it online. The response was overwhelming: I received hundreds of e-mails—some supportive, many not so much ("crackpottery" is a term I prefer). I even heard from people at NASA thanking me, including an Apollo astronaut who, I'll note, had in fact *walked on the moon*.

Online traffic to my review exploded. And it's no exaggeration to say it helped to launch my career as a science communicator and antiscience debunker. I went on to give public talks all over the world based on the ridiculous claims in the show.

But this came at a cost. The TV program was extremely popular, so much so that Fox reran it a few weeks later. I was extremely aggravated, as a space nerd and huge Apollo fan, to see one of the greatest achievements of our technological society dishonored in such a way.

Today, though, this conspiracy theory is mostly relegated to the waste bin; you hardly hear about it anymore. People have moved on. And that's the problem. Even at the time, when I gave my talks mocking the show and the conspiracy theory, I was careful to note that this type of antiscience thinking is dangerous. What if a politician—many of whom are not known for their grasp of science—were to buy into this nonsense and waste a vast amount of taxpayers' money and NASA's time investigating it?

I think about that with both a smug sense of pride at being correct and a big dollop of embarrassment for being so naive. Although a congressional investigation into NASA would have been a travesty, with hindsight I can say it also would have been one drop in a downpour.

Belief in UFOs—now called UAPs, or Unidentified Aerial (or sometimes Anomalous) Phenomena—tends to cycle in and out of popularity and is waxing again now. Despite the lack of any real evidence, the reliance on usually shaky videos of fuzzy objects widely explained as mundane sources such as balloons and airplanes, and laughably bad fake alien bodies, these claims appear to be taken seriously by a credulous media and even sometimes by government officials. If UFOs have taught us anything, it's that bad ideas never truly die. They just rebrand.

A more direct and bigger impact has been seen with the astronomical rise in anti-vax nonsense. That kind of thing has been around a long time, but in 1998 Andrew Wakefield, who would go on to be a disgraced former physician, published a study in the *Lancet* making a fraudulent link between vaccines and autism. This paper kicked off the modern anti-vax movement. Anti-vaxxers use many of the same types of bad logic and withholding of evidence as the moon-hoax show did.

Around that same time, creationists were making inroads into the public school system, thinly disguising their antibiology ideology as "intelligent design," or ID. The case *Kitzmiller v. Dover Area School District* brought this effort to national attention when creationists attempted to push an ID book as an alternative to a biology text in classrooms. Bad logic and withholding of needed evidence in their claims? Absolutely.

Of course, at the end of the millennium we had already been ensnared for decades in a long con by fossil-fuel industries, who downplayed the science of global warming as they actively encouraged the release of dozens of gigatons of carbon dioxide into our atmosphere every year. Climate science deniers make the Apollo deniers look quaint.

This list goes on. And at every step of the way, groups like these have been able to persuade politicians to back their views, sometimes encoding their antiscience beliefs into law. This crested in a tsunami of scientific disinformation during Donald Trump's presidency as his attacks on reality became so numerous they were nearly impossible to keep track of. His administration's mucking around with COVID, climate science, vaccinations, the Environmental Protection Agency ... all these and more had far-reaching domestic and international repercussions from which the world is still reeling.

Conspiracy thinking necessarily turns the scientific process upside down, settling on a conclusion first and then seeking evidence for it.

Conspiracy thinking necessarily turns the scientific process upside down, settling on a conclusion first and then seeking evidence for it while ignoring or attacking any evidence against it. This mindset is ripe for shaping by political groupthink, which amplifies closed belief systems, inuring them from outside remediation. Cultlike behavior, such as that of backers of the QAnon movement, may start as an outlier in such an environment but eventually become everyday ideology. We see it now from some members of Congress who were reelected in the midterms, showing that they still have support not only despite but because of outlandish things they believe and say. And do.

Obviously, the accusation that NASA faked the moon landings is not the cause of all these execrable and obviously false beliefs, but they go hand in hand. A willingness to believe such claims without evidence, to dismiss expert experience and to entertain conspiratorial ideas is at play here, and smaller, more "fun" ideas like the Apollo mission being a hoax are a foot in the door to a universe of nonsense. They may seem harmless, but they lead nowhere good.

This is the nature of the razor-thin path of scientific reality: there are a limited number of ways to be right but an infinite number of ways to be wrong. Stay on it, and you see the world for what it is. Step off, and all kinds of unreality become equally plausible.

As for my VHS tape, after my minute of reminiscing while I was packing up my house, I tossed it in the trash where it belonged. But a moment later, grimacing, I retrieved it. Garbage it may be, but it's also a symbol of what we must continue to fight and why. It now sits on my shelf, a reminder that a single virus particle may be small, but the infection it causes can still be dangerous. ●

This Unexpected Pattern of Numbers Is Everywhere

A curious mathematical phenomenon called Benford's law governs the numbers all around us BY JACK MURTAGH

OPEN YOUR FAVORITE social media platform and note how many friends or followers you have. Specifically, note the first digit of this number. For example, if you have 400 friends, the leading digit is 4, and if you have 79, it's 7. Let's say we asked many people to do this. We might expect responses across the board—common intuition suggests that friend counts should be somewhat random, and therefore their leading digits should be, too, with 1 through 9 showing up equally. Strangely, this is not what we would find. Instead we would see a notable imbalance with nearly half of the friend counts beginning with 1 or 2 and a paltry 10 percent beginning with 8 or 9. Remember, this isn't about having more or fewer friends; 1,000 friends is way more than eight.

This bizarre overrepresentation of 1 and 2 extends beyond friends and followers to likes and retweets and well beyond social media to countless corners of the numerical world: national populations, river lengths, mountain heights, death rates, stock prices, even the diverse collection of numbers found in a typical issue of *Scientific American*. Not only are smaller leading digits more common but they follow a precise and consistent pattern.

If all digits were represented equally, then they would each appear one ninth (about 11.1 percent) of the time. Yet in an uncanny number of real-world data sets, an astonishing 30.1 percent of the entries begin with a 1, 17.6 percent begin with a 2, and so on. This phenomenon is known as Benford's law. The law holds even when you change the units of your data. Measure rivers in feet or furlongs, measure stock prices in dollars or dinars—any way you measure, these exact proportions of leading digits persevere. Although mathematicians have proposed several clever reasons for why this pattern might emerge, its sheer ubiquity evades a simple explanation.

As it happens, Benford was not the first to discover Benford's law. Before calculators, people outsourced hairy arithmetic to reference books called logarithm tables. In 1881 astronomer Simon Newcomb noticed that early pages of logarithm tables, which correspond to numbers beginning with 1, were grubby and worn compared with the later pages. He deduced that smaller leading digits must be more common in natural data sets, and he published the correct percentages. Physicist Frank Benford made the same observation in 1938 and popularized the law, compiling more than 20,000 data points to demonstrate its universality.

The law has been used to put people behind bars. Financial adviser Wesley Rhodes was convicted of defrauding investors when prosecutors argued in court that his documents did not accord with the expected distribution of leading digits and therefore were probably fabricated. The principle later helped computer scientist Jennifer Golbeck uncover a Russian bot network on Twitter. She observed that for most users, the number of followers that their followers have adheres to Benford's law, but artificial accounts significantly veer from the pattern. Examples of Benford's law being applied to fraud detection abound, from Greece manipulating macroeconomic data in its application to join the eurozone to vote rigging in Iran's 2009 presidential election. The message is clear: organic processes generate numbers that favor small leading digits, whereas naive methods of falsifying data do not.

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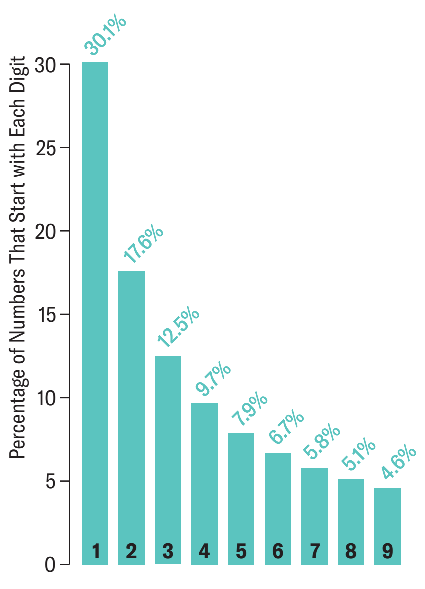
Why does nature produce a dearth of 9s and a glut of 1s? First, it's important to state that many data sets do not conform to Benford's law. Adult heights mostly begin with 4, 5 and 6 when measured in feet. A roulette wheel is just as likely to land on a number beginning with 2 as on one with 1. The law is more likely to apply to data sets spanning several orders of magnitude that evolve from certain types of random processes.

Exponential growth is a particularly intuitive example. Imagine an island that is initially inhabited by 100 animals, whose population doubles every year: after one year there are 200 animals, and after two years there are 400. Already we notice something curious about the leading digits. For the entire first year the first digit of the population of the island was a 1. In the second year population counts spanned the 200s and 300s in the same length of time, leaving less time for each leading digit to reign. This continues with 400 to 800 in the third year, when the leading digits retire faster still.

The reason is that growing from, say, 1,000 to 2,000 requires doubling, whereas growing from 8,000 to 9,000 is only a 12.5 percent increase, and this trend resets with each fresh order of magnitude. There is nothing special about the parameters we chose in the island example. We could begin with a population of 43 animals and grow by a factor of 1.3 per year, for example, and we

Distribution of Leading Digits in Many Real-World Data Sets



Source: "Note on the Frequency of Use of the Different Digits in Natural Numbers," by Simon Newcomb, in *American Journal of Mathematics*, Vol. 4, No. 1; 1881 (data)

Graphic by Amanda Montañez

would see the same exact pattern of leading digits. Almost all exponential growth of this kind will tend toward Benford's law.

The law's stubborn indifference toward units of measure gives another hint as to why the pattern is so common in the natural world. River lengths follow Benford's law whether we record them in meters or miles, whereas non-Benford-compliant data such as adult heights would radically change their distribution of leading digits when converted to meters because nobody is four meters tall. Remarkably, Benford's law is the only leading digit distribution that is immune to such unit changes.

We can think of changing units as multiplying every value in our data set by a certain number. For example, we would multiply a set of lengths by 1,609.34 to convert them from miles to meters. Benford's law is actually resilient to a much more general transformation. Taking Benford-compliant data and multiplying each value by a different number (rather than a fixed one such as 1,609.34) will leave the leading digit distribution unperturbed. This means that if a natural phenomenon arises from the product of several independent sources, then only one of those sources must accord with Benford's law for the overall result to. Benford's law is cannibalistic, much in the same way that a single zero in a bunch of numbers being multiplied together makes the result zero.

These explanations don't explain why the diverse collection of numbers plucked from an issue of *Scientific American* would adhere to Benford's law. These numbers don't grow exponentially, and we're not multiplying them together. Mathematician Ted Hill discovered what many consider to be the definitive proof of the leading-digit law. He argues that if you pick a bunch of random numbers from a bunch of random data sets, they will tend toward Benford's law. In other words, although countless data sets show Benford's pattern, the most reliable way to manifest it is to pull numbers from varying sources, such as those we see in a newspaper.

I've spent a lot of time thinking about Benford's law, and it still surprises me how often it shows up. Pay attention to the numbers you encounter in your daily life, and you might begin to spot examples of it.

Will AI Worsen Inequality?

A Nobel laureate in economics explains how artificial intelligence will affect the workforce

BY SOPHIE BUSHWICK

FOR THE FIRST TIME since the 1960s, Hollywood writers and actors were on strike concurrently this past summer. One of the joint movement's motivating factors was generative artificial intelligence—the term for programs that produce humanlike text, images, audio and video more quickly and cheaply than artists can. The strikers feared studios' use of generative AI tools would replace or devalue human labor. This is a reasonable worry: one report suggests that thousands of jobs have already been lost to AI, and another estimates that hundreds of millions could eventually be automated. Left unchecked, this labor disruption could further concentrate wealth in the hands of companies and leave workers with less power than ever.

"Unfettered capitalism, unfettered innovation, does not lead to the general well-being of our society," says Joseph E. Stiglitz, a winner of the 2001 Nobel Prize in economics, a professor at Columbia University, and chief economist at the Roosevelt Institute, a think tank based in New York City. "That's one of the results that I've shown very strongly. One can't just leave it to the market." Striking workers could serve as one restriction on job automation. Government regulation also could limit AI's disruptive ability. Stiglitz, who has studied the science of inequality—and how we can reduce it—spoke with SCIENTIFIC AMERICAN about how AI will affect the U.S. economy and what should be done to prevent it from increasing economic inequality.

An edited transcript of the interview follows on the next page.

Illustration by Shideh Ghandeharizadeh

Generative AI is already disrupting the job market. Copywriters have been laid off in favor of text-generating programs such as ChatGPT. IBM has said it will pause hiring on thousands of roles that could be done by AI. Do you see this trend continuing?
Yes, I do. But we don't know the extent to which it will happen. I think it will replace people in more routine jobs—you mentioned copywriting, copyediting. Where there are a set of rules, it can read and see whether those rules are followed. It may not have as good an eye for the exceptions, and so I think there's going to be a lot of AI-human interfacing: people will use AI as a productivity-enhancing tool.

Somebody trained ChatGPT on my data, and I tested it to see how well it did in answering questions from a journalist. I made up the questions, and I reviewed the answers. I thought on half the questions it did perfectly reasonably—and on three it was totally wrong. So I think my view is that it's not going to be unleashed without a lot of human interaction. You're going to have to check it—not only the quality of the answer but also the bias and whether it's gone down a rabbit hole and produced made-up references.

What about the possibility of AI creating jobs? Would that be enough to make up for some of the jobs that will disappear?
No, I don't think so. I think it's going to create a demand for different skills. AI is very much like a black box. By that, I mean even the people who create it don't understand exactly how it's functioning. So at least some people have speculated that managing an AI may require more linguistic humanities skills than mathematical skills. And it may create a change in the kinds of skills that are valuable in the labor market. I see it as, at least in many areas, increasing productivity enough that the demand for labor in those areas will go down. There will be jobs created, but my judgment is that there will be more jobs lost.

Could we end up in a situation where human-created work is a premium product, the way buyers might be willing to pay more for hand-woven sweaters than for machine-made ones?
Yes, there's a widespread sense that there's a kind of blandness to ChatGPT-generated material. There's always going to be a demand for creativity. I think the areas where it's going to replace us are very much the areas where, now, we don't put a lot of weight on who has written it—you know, it's a newsletter or something that, if it had been generated by a machine, we don't care.

As someone who studies inequality extensively, how do you see these changes in the job market contributing to inequality?
I'm very worried. In a way, robots have replaced routine physical work. And AI now is replacing routine white-collar work—or not replacing it but reducing the demand. So jobs that were routinely white collar, I think, will be at risk. And there are enough of those that it would have a macroeconomic effect on the level of inequality. It could amplify the sense of disillusionment.

Now, that poses an advantage and a disadvantage. It may mean that large fractions of the world, of the U.S., will face this inequality. On the other hand, if we get our macroeconomic policy right and create jobs, the jobs will be created everywhere. People won't have to move in the way they do right now, when the jobs that are created are in urban coastal cities, and the jobs that are lost are in the Midwest, the South, industrial towns. So some of the place-based inequality, which has played such a role in the divided U.S., may not be as bad.

And do you see any potential solutions to this issue of reduced demand for white-collar work?
Sure, two things: We increase aggregate demand to keep the economy closer to full employment, and we have active labor-market policies to train or retrain people for the new jobs created by AI. It may be that if we have good, distributed policies, people may say, "Well, our standard of living is sufficiently high—I don't need that many material goods." They'll accept more leisure; we might move to a 30-hour week. In effect, our measured GDP [gross domestic product] would not be as high as it would be if we had a 35- to 40-hour week. But our objective is not measured GDP; our objective is well-being. It could well be that we decide to move to an equilibrium with overall shorter working weeks and more leisure. And that may be one way we accommodate this increased productivity and increased innovation.

How can we incentivize companies to shorten the workweek and accept reductions in overall profitability?
We may have to use government regulation because of the weakness of the bargaining power of workers—especially in the U.S. We passed the "hours and wages bill" [the Fair Labor Standards Act of 1938] in the Great Depression, which capped the workweek at 40 hours. That was a long time ago, and now we're in a new world. It may be the appropriate thing is to set it at 30 or 35 hours with a lot of flexibility, so if companies want to have the workers work more than that, then they pay them overtime.

What we must recognize is that we created a system where workers don't have much bargaining power. In that kind of world AI may be an ally of the employer and weaken workers' bargaining power even more, which could increase inequality even more. There is a role for government to try to steer innovation in ways that are more productivity-increasing and job-creating, not job-destroying.

Overall, do you feel optimistic or pessimistic about the situation with AI in the workplace?
I guess overall I feel pessimistic with respect to the issue of inequality. With the right policies, we could have higher productivity and less inequality, and everybody would be better off. But you might say that the political economy, the way that our politics have been working, has not been going in that direction.

So at one end I'm hopeful that if we did the right thing, AI would be great. But the question is: Will we be doing the right thing in our policy space? That's much more problematic. ⬣

Sophie Bushwick is an associate editor covering technology at *Scientific American.*

Restoring the Road to Opportunity

Media attention to Ivy League schools distracts from the much more important—and undersupported—public university system **BY NAOMI ORESKES**

ONE OF THE BIG academic stories of 2023 was the U.S. Supreme Court's decision to end the use of race as a criterion in college admissions. The ruling was based on two cases that made their way to the high court, one focused on Harvard University and the other on the University of North Carolina.

Most of the media attention and commentary centered on Harvard. Former president Barack Obama, who attended Harvard Law School, defended the university's policies as allowing Black students to prove that "we more than deserved a seat at the table." Michelle Obama, who also attended Harvard Law School, wrote that her heart was breaking for "any young person out there who's wondering what their future holds—and what kind of chances will be open to them." Reporting on an analysis of admissions data, the *New York Times* noted the many ways that Harvard continued to be a bastion of privilege whose admissions criteria "amounted to affirmative action for the children of the 1 percent."

The focus on Harvard was misplaced, however. If the issues at stake are opportunity and its role in a democratic polity, then our focus should be on supporting and strengthening the public university system. Of the 14 million American students in four-year schools, about two thirds are in public schools, where the ethnic and racial makeup is much closer to the overall undergraduate population than it is at private schools, as well as close to the U.S. population in general. In these schools the largest obstacle to advancement is cost.

The past decades have seen huge increases in costs at public institutions of higher education. Measured in constant dollars, in the 1963–1964 academic year, tuition, room and board at four-year public institutions was $8,491. By 2021–2022 that figure was $21,878—almost three times as high. Declining state support is a major contributor to rising fees—and not just in "red" states. At the University of California, San Diego—where I taught for many years—the share of revenues that came from state support declined from 32 percent in 2002 to 15 percent in 2020; similar patterns can be found broadly. According to the National Education Association, "across the U.S., 32 states spent less on public colleges and universities in 2020 than in 2008, with an average decline of nearly $1,500 per student. As a result, students need to pay (and borrow) more."

In the wake of the COVID pandemic, some states have increased their support, but overall, funding for public colleges dropped 9.1 percent from 2008 to 2018. The net effects of decreased public funding are an increased burden on students and, except for the very wealthy, diminished educational opportunities.

Budget cuts don't lead just to higher fees, which some students could perhaps address by working more hours in the dining hall or borrowing more money. Underfunding also results in fewer career options. West Virginia University recently announced that, because of budget cuts, it will no longer teach world languages and creative writing, curtailing options for students hoping for careers in foreign service, immigration law, journalism, and many other fields. Furthermore, underfunding leads state officials (and sometimes, in response, university administrators) to promote a narrow, vocationally oriented view of education, which further restricts students' options.

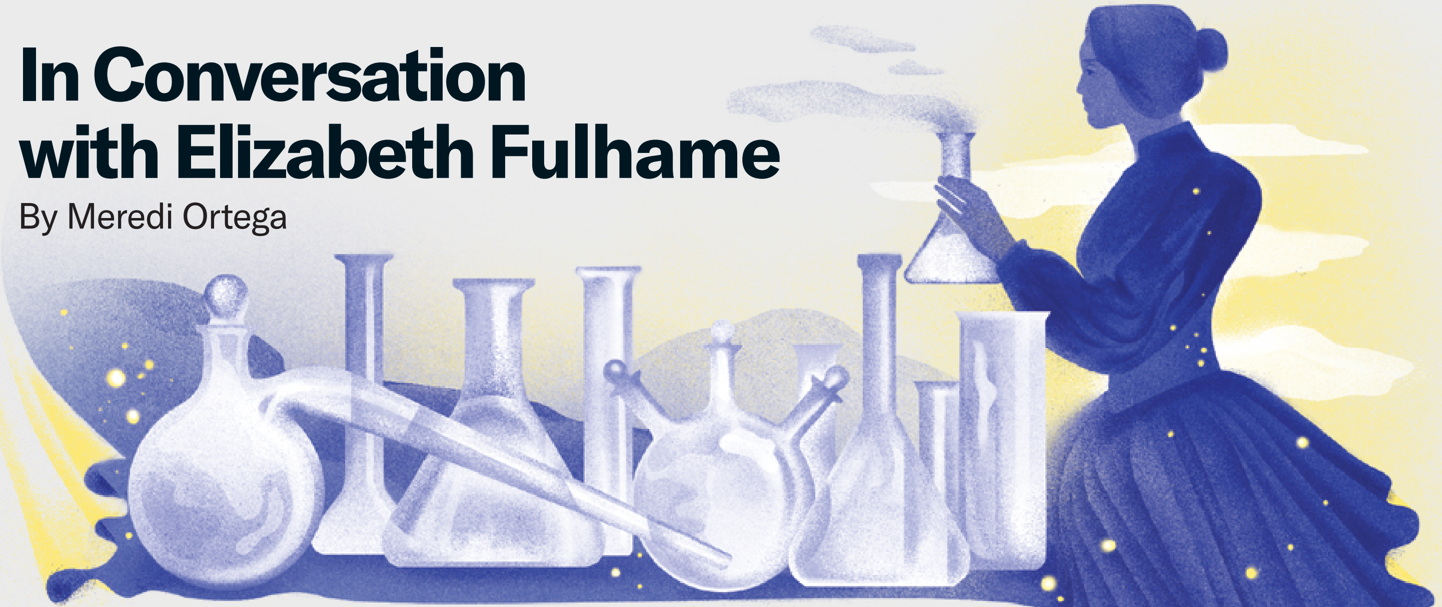
In 1970 most jobs did not require a college degree. Today nearly all well-paying ones do. With the rise of artificial intelligence and the continued outsourcing of low-skilled and de-skilled jobs overseas, that trend most likely will accelerate. Those who care about equity of opportunity should pay less attention to the lucky few who get into Harvard or other highly selective private schools and more to public education, because for most Americans, the road to opportunity runs through public schools.

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and coauthor of *The Big Myth* (Bloomsbury, 2023).

Illustration by Izhar Cohen

In Conversation with Elizabeth Fulhame

By Meredi Ortega



She has a map spread at her feet, a lit carpet of gold cities
and silver rivers, each tributary wire-drawn with the tip
of a squirrel's tail. Everything is very damp.

It seems like a dream, even in the dream. Saucers of silk
line the sills like a grand banquet for clothes moths.
The round table (pocked with scorch marks) throngs

with china cups of phosphorus in ether, tin dissolved
in muriatic acid, white oxide of arsenic in—
She tongs sugar lumps, pours the pot. Rainbow bull's-eyes

float in our cups like latte ferns. The ceiling drips.
On the reading stand, a well-thumbed book on phlogiston
is flapping its mildewed wings. The room is strewn

with glittering retorts, cylinders, phials. She wants to know
her name because, for so long, she's been vanishing
by degrees. "The facts of me escape me," she says.

She lifts the lantern of Dr. Nooth's machine. Iron nails
and diluted sulfuric acid at glass bottom. In the middle,
a ghostly snip of lead-dipped silk dangles over water.

Spangled silver by spindrift, it's the sail of an invisible craft.
There's a puff of white smoke, a never-ending string
of silk swatches from her sleeve. A little goes a long way

and this show might just go until dawn. Now the clouds
are lifting, the wallpaper is rolling back in waves.
It's less drawing room, more Marie Antoinette's bedroom.

In the golden aquatic, our chairs, napkins and clothes blaze
ablaze with shiny, shiny. She says it always consumes her
with wonder, yet her wonder is never consumed.

I imagined in the beginning,
that a few experiments
would determine the problem

they grow sullen and silent,
and are chilled with horror
at the sight of any thing

that bears the semblance
of learning, in whatever shape
it may appear; and should

the specter appear in the shape
of woman, the pangs which
they suffer are truly dismal

Combustible bodies, as
hydrogen, phosphorus,
sulfur, charcoal, light, &c.

are capable of reducing
the metals in the ordinary
temperature of the atmosphere

so that a thimble full
of water would be sufficient
to reduce any quantity of metal

for this little bark of mine
has weathered out full
many a storm

repeated times unnumbered
so bright and dazzling
as to distress the eye

Meredi Ortega is an Australian poet living in Aberdeen, Scotland. Her poems have appeared in *The Best Australian Science Writing 2023*, *Meanjin*, the *Poetry Review* and the *Times Literary Supplement.*

In the 18th century chemist Elizabeth Fulhame described the processes that later became known as catalysis and photoreduction. Extracts in italics are from her 1794 work: "An Essay on Combustion with a View to a New Art of Dying and Painting, Wherein the Phlogistic and Antiphlogistic Hypotheses are Proved Erroneous." This essay was reprinted in 1810 in Philadelphia. It's not known where or when she was born. According to a note by Charles Watt, Fulhame "died in abject poverty in a mean apartment in the vicinity of Soho Square."

Illustration by Masha Foya

Quantum Consciousness

How the quest to know our mind is central to understanding our physical universe

BY PITCHAYA SUDBANTHAD

NONFICTION For a time, in the late 1980s, it looked like the field of neural networks was dead. Its researchers, who were seeking answers about consciousness by creating interconnected webs of computing units, could not overcome the limitations of their tools. Hardware did not compute at fast enough speeds. Software was too simplistic. It wasn't until the 2010s that technology had advanced far enough to allow theories "that seemed almost frozen in amber" to be explored further.

That scientists could leap far ahead into new theoretical territory yet make little experimental progress in computational neuroscience underlines the challenges and complexity in explaining the workings of mind and consciousness. In *Putting Ourselves Back in the Equation,* journalist and *Scientific American* contributor George Musser brings readers along on this quest, tracking the development of different ideas and suppositions that aim to elucidate how consciousness might have arisen and what processes inform—if not create—our perceptions of reality.

Investigating the mind and confronting the "hard problem" of consciousness necessarily require the collision of disciplines. The field's most significant researchers seem to have stumbled into it from myriad backgrounds—semiconductors, psychiatry and cosmology, among other fields—and it's Musser who wanders into these scientists at conferences, in cafeterias and in train cars to get details on the latest findings. His book is structured as an overview in the form of an expansive series of questions. It begins with the mechanical and local—say, how a brain might anticipate information—and progresses toward ones that threaten any simplistic notion of reality, such as: What if we're only a floating blob mind that briefly materializes in the death throes of a universe?

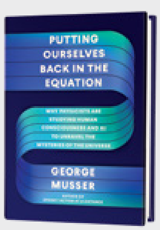
It's no surprise that the study and building of neural networks have become central to learning about the mind. Unlike simple computers, these networks can involve many parallel systems of interwoven logic, much like our brain and its wiring. Simulated neurons in a network, for instance, allow for the dynamism of feedback, enabling the network to form associations and learn algorithmically. What we consider as consciousness could be an emergent property of these highly organized, interconnected systems.

Musser takes two leading theories of mind that have emerged from the study of these networks as avenues of exploration and explanation. Karl Friston's predictive coding theory says that our consciousness arises from the constant updating of a processing pipeline that both receives and predicts information—that is, our expectations also make our reality. Meanwhile Giulio Tononi's integrated information theory proposes that consciousness is the result of neural networks working together in harmony. It's the systemic unity that unleashes an emergent property of conscious awareness greater than the underlying parts alone.

These two theories recurrently pop up in the book as Musser reveals that our quest to understand our mind is also a fundamental investigation of the physical universe we believe we know. It turns out that our subjective consciousness appears to have a big role in the finer workings of physics at large—especially at the quantum level, where there may be no objective outcomes, only subjective experiences. Two philosophers, David Chalmers and Kelvin McQueen, have suggested that the mind itself creates a quantum collapse effect. Others, of course, disagree. One cognitive scientist thinks it happens the other way around—that the collapse effect is what creates consciousness.

Musser shows that prodding at the level of infinitesimal quantum phenomena uncovers larger questions that require a fuller understanding of our consciousness. Is there an objective reality, or is it all in our heads? Is there such a thing as free will? Is spacetime only a projection of our brain's neural processes?

It's possible that we inhabit a perspectival universe dependent on the presence of an observer. It's possible for us to attain agency and a sense of causality at a high level of organization that frees us from the utter chaos of particle particulars. It's possible that we cannot remember the future, because our memories need to first become quantum entangled with our world. We think, therefore, we're possibilities nested within probabilities. In thinking about thinking, many devoted thinkers get seemingly trapped in thought experiments in a strange, self-contradicting loop. When in doubt, cry "empirical incoherence" and make a run for it.



Putting Ourselves Back in the Equation: Why Physicists Are Studying Human Consciousness and AI to Unravel the Mysteries of the Universe by George Musser. Farrar, Straus and Giroux, 2023 ($30)

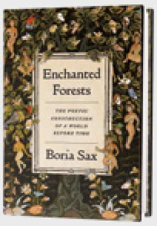
Pitchaya Sudbanthad is author of *Bangkok Wakes to Rain* (Riverhead, 2019), a *New York Times* and *Washington Post* notable book of the year.

Illustration by Alex Eben Meyer

Woodland Mythos

The powerful symbolism of forests

NONFICTION The word "forest" came into English from medieval French, where it meant a place reserved for the king's hunt. Poachers who violated this divine gift to royalty were punished, sometimes by death. Forests, then, are social constructions as well as communities of trees. "Every conception of the forest is a kind of cosmology," writes author Boria Sax in this fascinating meander through the rich woodlands of literature and visual art.



Enchanted Forests: The Poetic Construction of a World before Time
by Boria Sax.
Reaktion, 2023 ($35)

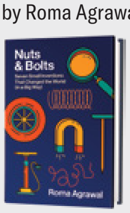
Sax shows that forest tales reveal how we imagine time. Trees are at the center of origin myths such as Buddha's enlightenment and Adam and Eve's temptation. In Norse, Mayan and Zoroastrian traditions, the first humans were trees transformed into people. From the *Epic of Gilgamesh* to the *Aeneid,* the arc of "civilization" emerges from and then conquers woodland. Forests are also home to allegorical stories about people's lives, such as the "savage, bitter and intense" woods of Dante's midlife and the rites of passage that unfold in fairy tales.

As farms and cities expanded, forests got pushed into the imagination, where they took on powerful symbolic roles. Sax highlights the contradictory nature of mythic forests: places of both Edenic innocence and terrifying chaos. These "enchanted" imaginings became enablers of human injustice and ecological despoliation. For European colonists, American, Asian and African forests were frightening and primeval. Progress, they thought, demanded that forests be cleared of trees and Indigenous people, an idea that still drives land theft in many parts of the world.

For some writers today, forests are communities of cooperative talking trees. Others see competitive individualism, each trunk a reminder of the Darwinian struggle for life. Forests are imagined as numbers, too: metric tons of carbon or cubic meters of timber. Sax reminds us that these symbols and projections change how we treat one another and the land. Implicit is the challenge to rethink our stories. Are we like medieval kings, taking the forest by right, or can we find narratives of reciprocity with forests and forest-dwelling cultures? *—David Haskell*

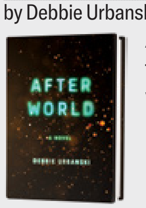
IN BRIEF

Nuts & Bolts: Seven Small Inventions That Changed the World (in a Big Way)
by Roma Agrawal. W. W. Norton, 2023 ($29.99)



"How does a refrigerator work?" a classmate once asked in my high school physics class, derailing the lesson as we tried to identify fundamental components and forces. *Nuts & Bolts* seems written for such thinkers and tinkerers. Enlivening the history and engineering principles behind seven key inventions are examples that span the mundane to the extraordinary: wheels enable dishwashers as well as the International Space Station; pumps make water faucets and space suits possible. If you delight in dissecting the whole, author Roma Agrawal places great cultural and philosophical value on scrutinizing the parts. *—Maddie Bender*

After World: A Novel
by Debbie Urbanski. Simon & Schuster, 2023 ($27.99)



After an artificial superintelligence targets humanity with a sterilization virus, it invites the last people to have their "post-body" lives preserved and uploaded to a new virtual world through the Digital Human Archive Project (DHAP). One "storyworker" called ad39-393a-7fbc is tasked with converting the life and death of a young woman into an optimized narrative format, but as it synthesizes journals, transcripts and reference texts chronicling her harrowing experience of the Great Transition's violent social collapse, it struggles to maintain the authorial distance that DHAP requires. This inventive love story is meticulously experimental with time and structure. *—Dana Dunham*

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The COVID Baby Bump

The pandemic affected birth rates in the U.S. in several ways

TEXT BY TANYA LEWIS
GRAPHICS BY AMANDA MONTAÑEZ

BIRTH RATES TEND to decline during economic recessions or disasters, so many experts predicted that the COVID pandemic would prompt people to have fewer children. A recent study of fertility trends in the U.S. from 2015 through 2021, however, reveals there was actually a baby bump.

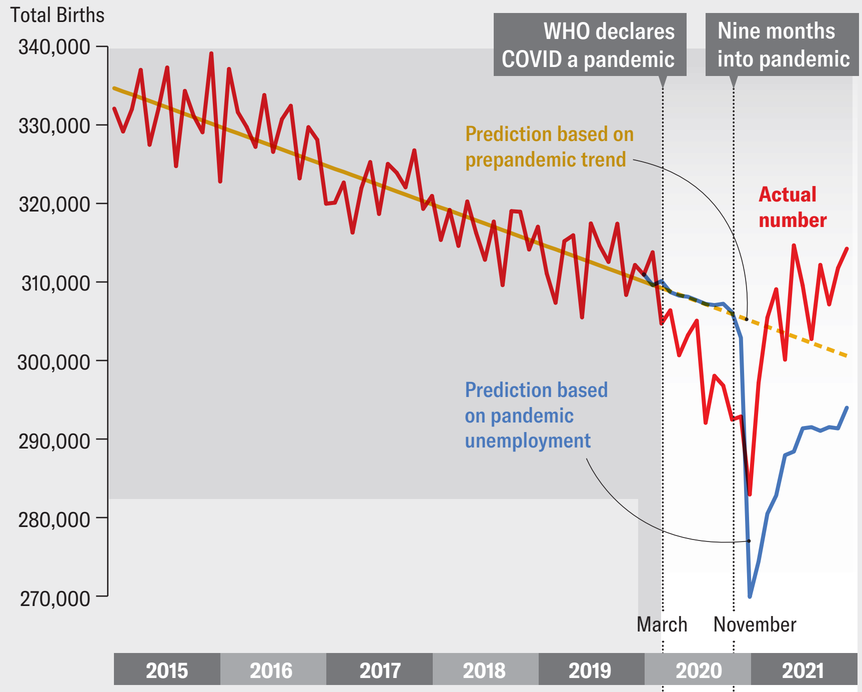
Demographers expected to see a decline in birth rate in December 2020, nine months after COVID became a pandemic. But the decline started earlier than that. It was driven largely by a drop in births to people born outside the U.S.—especially people from China, Mexico and Latin America—who would have traveled here but were prevented by pandemic restrictions. Some of them would have been coming as immigrants, whereas others would have been visiting to secure U.S. citizenship for their babies before returning home.

In 2021 the birth rate bounced back even more than predicted. This reversal is attributable mainly to an increase in births to mothers born in the U.S. (except among Black women). The biggest increases in births occurred among women younger than 25 and those having their first child. Among women older than 25, the largest upticks in births were for those aged 30 to 34 and those with a college education. Because there is a lag in data on births, these results do not include the most recent trends. But data from California suggest births were still increasing as of early 2023.

Study co-author Janet Currie, an economist at Princeton University, speculates that working from home (for those who were able to) gave people more flexibility to start a family. In other words, Currie says, "if you made it easier for people to have children, maybe more of them would."

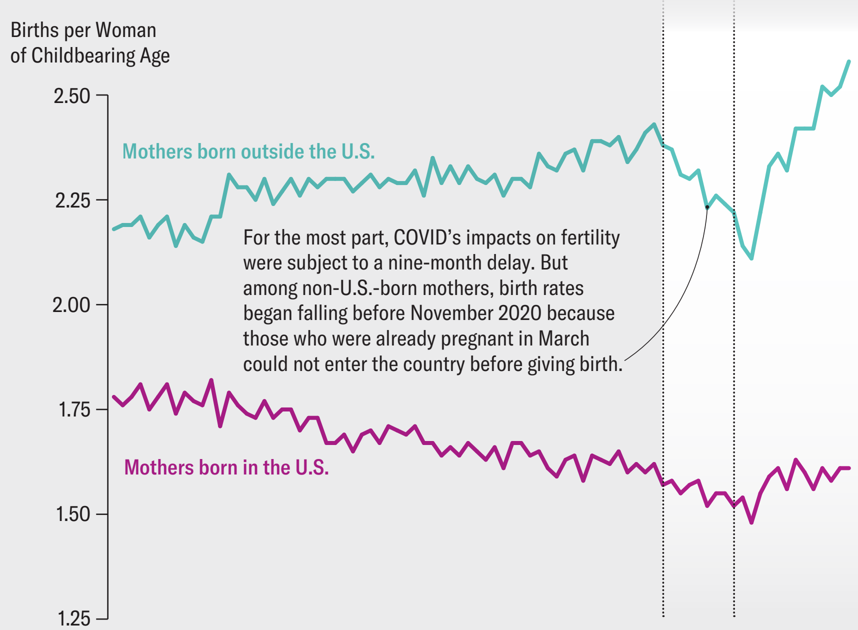
NUMBER OF U.S. BIRTHS

The number of babies born from one month to the next is variable but tends to follow a fairly predictable pattern. Researchers suspected that COVID's economic impacts would alter this pattern, but surprisingly, the 2020 dip in births was not proportional to the rise in unemployment. And in 2021, the numbers rebounded sharply, making the net loss in births less severe than expected.

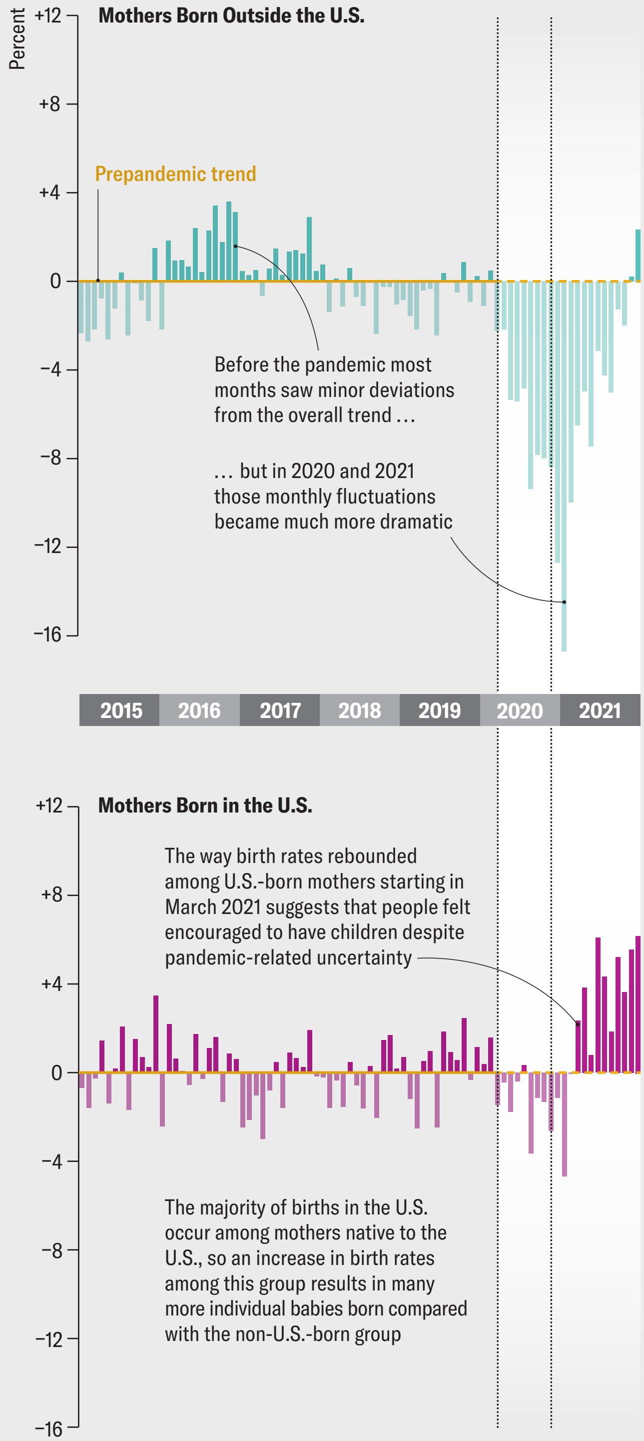


U.S. TOTAL FERTILITY RATES

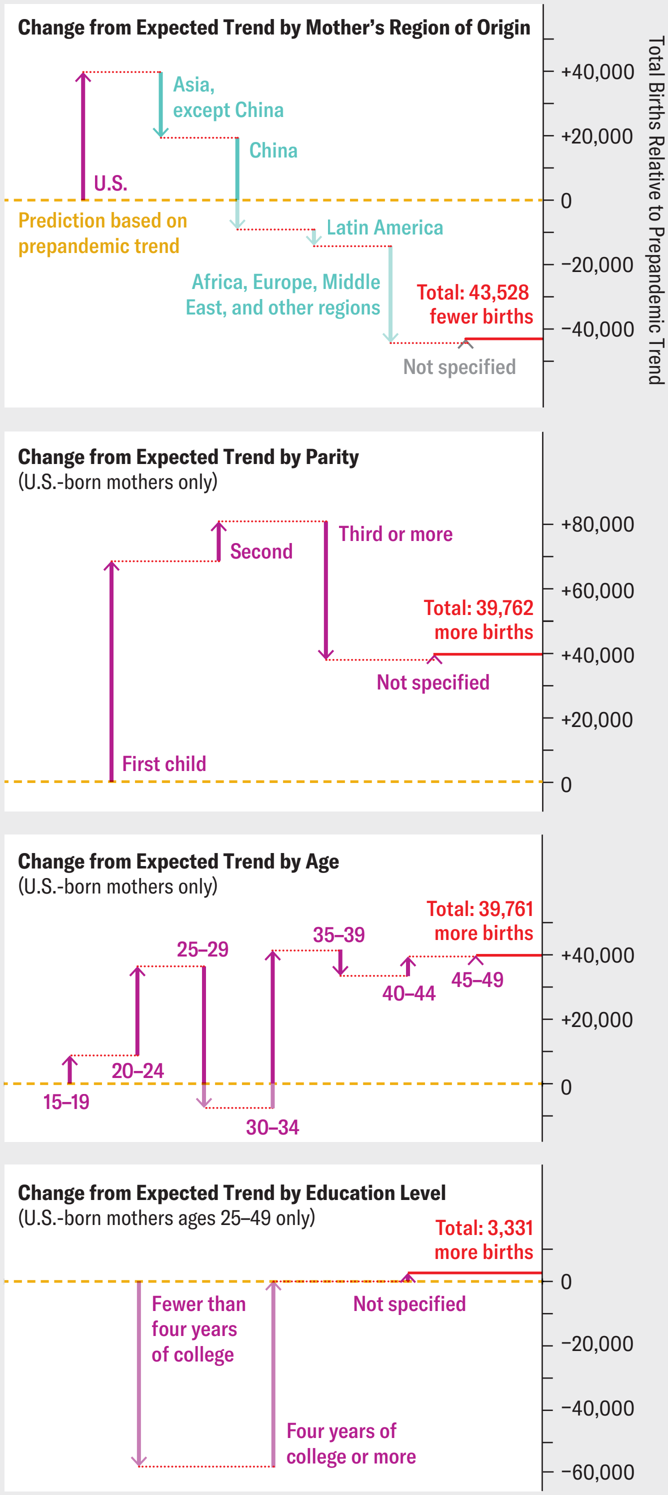
Total fertility rate measures the expected number of children a woman will have in her lifetime based on current trends. In 2020 U.S. fertility fell to a record low, but the decline was largely driven by pandemic border restrictions, which kept those in other countries from giving birth in the U.S. Among U.S.-born mothers, fertility experienced a net increase from the start of 2020 to the end of 2021.



CHANGES FROM EXPECTED TRENDS
To measure COVID's effects on birth rates, it is useful to compare data from each month with what researchers think those numbers would have looked like had prepandemic trends continued. Since about 2007, U.S. fertility has been falling steadily. The pandemic initially seemed to amplify this trend, but among U.S.-born mothers, 2021 saw a "baby bump" of 5.1 percent above pre-COVID estimates.

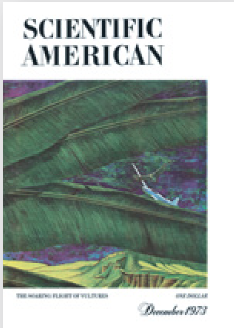


HOW CHANGES VARIED AMONG SPECIFIC GROUPS
These charts show how birth rates shifted in different ways for different demographic groups. Each of the specified subgroups pushed the numbers up or down to arrive at a net gain or loss in total births over the 2020–2021 period, compared with pre-COVID predictions.



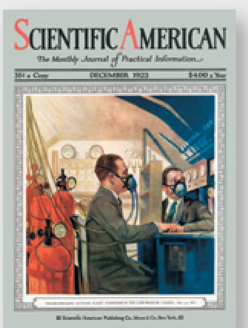
Source: "The COVID-19 Baby Bump in the United States," by Martha J. Bailey, Janet Currie and Hannes Schwandt, in *PNAS*, Vol. 120; August 15, 2023

50, 100 & 150 Years



NOBEL PRIZE WINNERS, NO PH.D. NEEDED

1973 "The 1973 Nobel prize in physics was awarded to Leo Esaki and Ivar Giaever 'for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors respectively,' and to Brian Josephson 'for his theoretical predictions of the properties of a supercurrent through a tunnel barrier.' Tunneling occurs because particles have the properties of waves; such waves do not stop abruptly at a barrier but penetrate some tiny but measurable distance. It is remarkable that all three of the recipients did their prizewinning work before they had received their doctorate."

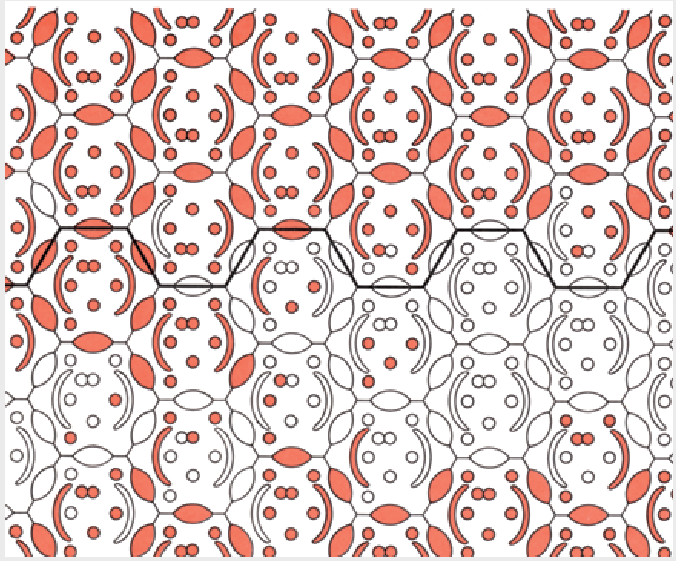


EDISON INSPIRED BY GAS LIGHTING

1923 "There are 350,000,000 incandescent lamps in the U.S. and about an equal number in foreign countries. When Edison first studied incandescent light, commercial arc lights operated on the 'series' system, the only system for distributing electricity known. Current generated in the dynamo flowed through the field coils, out to one lamp after another over a wire, then back to the dynamo. One lamp could not be turned on or off without doing the same with all the others. Edison realized it never would be satisfactory for household lighting. He decided to pattern electric lighting after gas lighting, with which it would compete. He reasoned that a constant-pressure system could be made similar to that of gas. In 1879 he made a dynamo which met every requirement, and a carbon lamp in which the filament consisted of a carbonized piece of ordinary thread. On October 21, 1879, current was turned into the lamp and it lasted forty-five hours. All incandescent lamps today embody the original features."

THE DEEPEST MINE

"The deepest hole in the earth is a gold mine in Brazil, known as the Morro Velho or St. John del Rey mine. The St. John del Rey Mining Company has been working it almost continuously since 1834. The mine is now 6,726 feet below the surface. The temperature of the rock at the lowest level is 117 degrees. The miners work in an air temperature of 98 degrees. The outside air has an average temperature of 68 degrees, but is cooled to 42 degrees before being forced to the lowest levels by powerful fans. On its way it gains heat from the rocks and from its own compression, because air at that great depth is considerably denser than air at sea level."



1973, Fly's Eye: The eye of a mosaic fly (which has original and mutant genotypes) "is an array of hexagonal ommatidia, each containing eight photoreceptor cells (*circles*) and two primary pigment cells (*crescents*), surrounded by six shared secondary pigment cells (*ovals*). The fact that a single ommatidium can have white and normal genotypes shows its cells are not necessarily descended from a common ancestral cell."

IMPERVIOUS SUN WILL KILL US ALL

1873 "The *New Orleans Picayune* tersely gives the results of the learned scientific Americans who lately met in Portland. 'Professor Young tells us that the sun is nothing but a gigantic spherical mass of gaseous matter, which is constantly being contracted by the gradual cooling of its outside circumference. The central kernel of this huge star will always finally be crusted over with a thick, impervious coating, through which neither light nor heat can possibly reach us. The result, as far as we are concerned, will be total darkness, intense cold, the end of animal life and a return to primeval chaos.'"

COMPETING ROUTES FOR PANAMA CANAL

"The Secretary of the Navy states that the two expeditions authorized by Congress to survey a canal route between the Atlantic and Pacific Oceans have finished their labors. The Darien expedition has selected a route including 100 miles of river navigation of the Atrato. Between this river and the Pacific a canal is necessary, 28 miles in length. The Nicaragua expedition has determined a practicable route having Lake Nicaragua as its summit. It is proposed to connect this lake with the Pacific by a canal 16.33 miles in length; an independent canal 41.9 miles in length is needed. The Darien seems to be much more direct and easier to construct."
In 1902 the Isthmian Canal Commission decided on a third route, which became the Panama Canal of today.

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"Modernizing Nuclear Weapons Is Dangerous," by the Editors [Science Agenda], should have said that the so-called nuclear sponging mapped in "Sacrifice Zones," by Sébastien Philippe, would kill up to several million from radiation exposure, not 90 million in the first two hours. The latter figure regards a 2019 estimate of the number of people killed within the first few hours of a nuclear war between Russia and the U.S.