SCIENTIFIC AMERICAN

Growing the Adolescent Mind

Recycling Space Junk

Redefining Alzheimer's

A Cellular Revolution

Long-overlooked molecular blobs are transforming our understanding of how life works

FEBRUARY 2025
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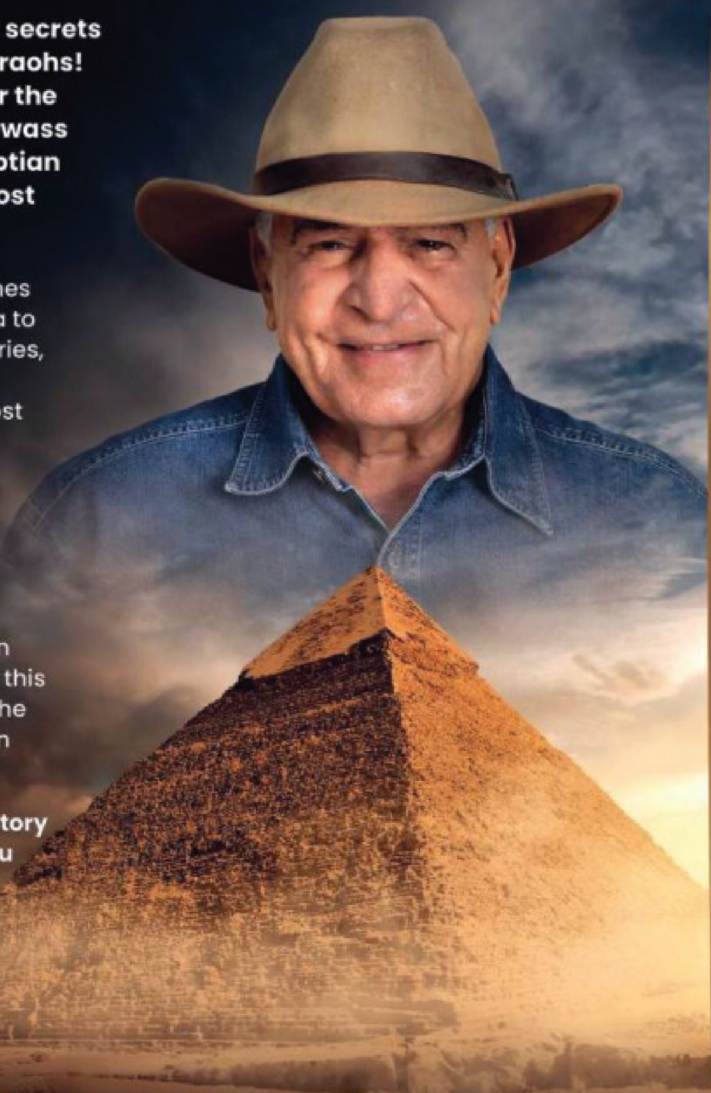

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SCIENTIFIC AMERICAN

NASA, ESA, CSA, STScI, Danny Milisavljevic/Purdue University, Ilse De Looze/University of Ghent, Tea Temim/Princeton University

ON THE COVER
Tiny blobs called biomolecular condensates were long overlooked in cell biology. But recently scientists have discovered that these membraneless, shape-shifting specks play a vital role in just about every aspect of cellular function. Condensates are now revealing a new scale on which life organizes itself and a surprising dynamism of molecular coordination.

Illustration by Mark Ross

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LinP74/Getty Images

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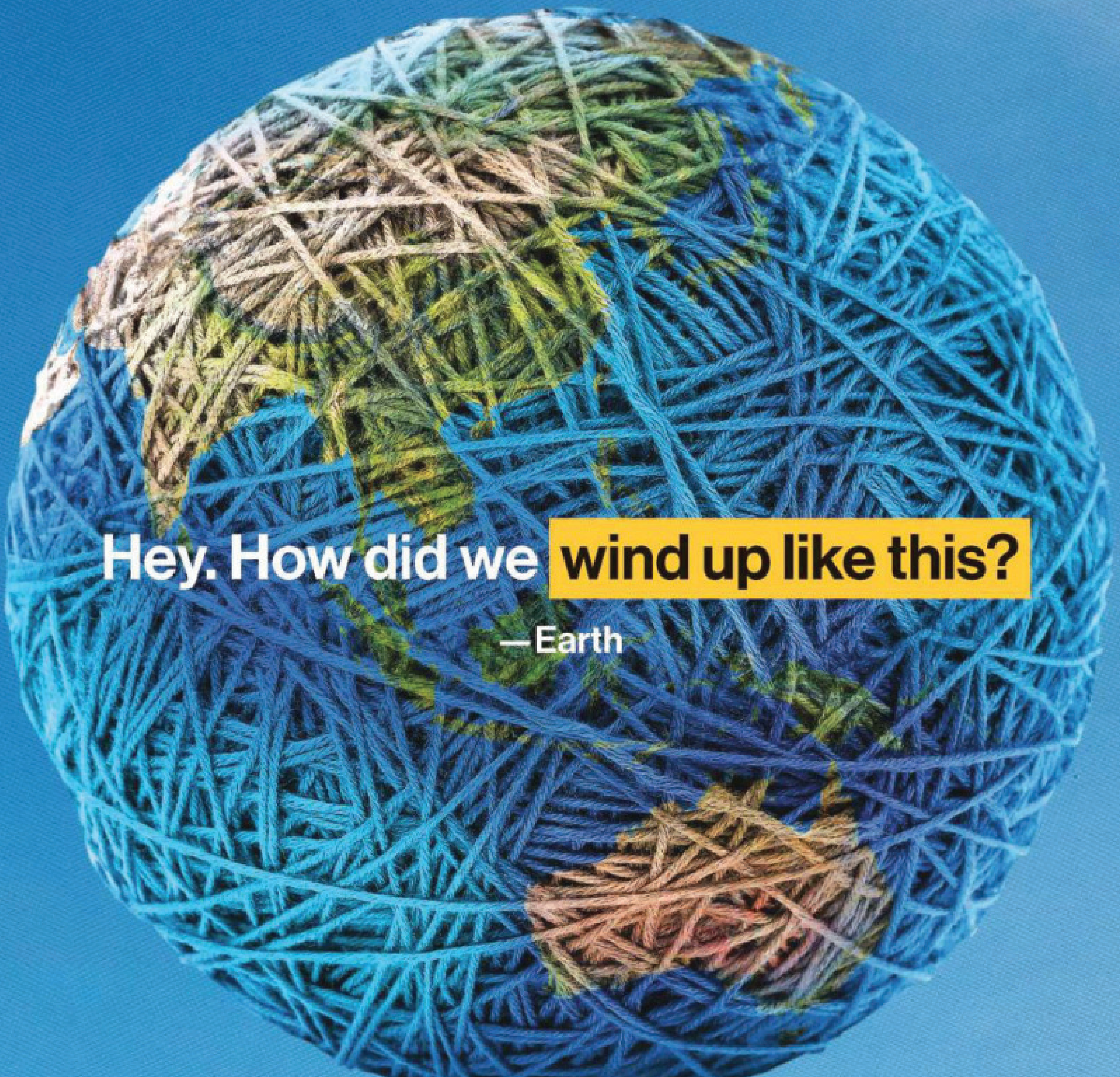
Hey. How did we wind up like this?
—Earth

Blobs and Green Monsters

DO YOU REMEMBER LEARNING about cell diagrams in high school biology? The cell wall, the organelles, the nucleus. The real picture is turning out to be much more complicated, and interesting, than we were taught. Cells are filled with teensy, phase-shifting blobs that often contain protein and RNA, and in the past several years they've taken over cellular biology. In our cover story on page 22, science writer Philip Ball dives into the world of these specks, known as biomolecular condensates, which play astounding roles in cellular functioning across all domains of life. But when they go awry, researchers suspect they may lead to the tangled protein clumps behind some neurodegenerative diseases. Scientists are now looking into just how these blobs tick, what forms they take and how they might be leveraged for medical advances.

Teens are eternally trying to make sense of the world and find their place in it. This endeavor requires flexible shifts between two different brain circuits, one for immediate, focused thinking and the other for reflective pondering. On page 48, neuroscientist Mary Helen Immordino-Yang describes how teens' proclivity for such transcendent and deep thinking leads to brain development and greater life satisfaction. The good news: parents and teachers can give adolescents mental space to travel in time, grapple with big questions and build their own narratives, resulting in brighter young adults with brighter futures.

The medical field is reconsidering the definition of Alzheimer's disease. Until recently, doctors assessed people for the illness mainly by using subjective cognitive tests. Now, genetic counselor Laura Hercher explains (*page 56*), blood tests that look for telltale biomarkers can indicate someone has the pathology well before the onset of symptoms. The advancement has led scientists to debate whether someone with only biomarkers and no symptoms should get an Alzheimer's diagnosis. The answer has knotty implications, Hercher points out: "Would you go to a surgeon or hire a lawyer who was biomarker-positive for Alzheimer's disease?" On the flip side, what if the field advances to the point of prevention? Then a doctor might be able to treat a person with "pre-Alzheimer's." As my mom suffers through mid-stage Alzheimer's, I'm watching every advance with hope for a future where the disease becomes preventable and treatable.

The James Webb Space Telescope continues to deliver gorgeous views of our universe. Senior space and physics editor Clara Moskowitz (*page 62*) takes us on a tour of a recent JWST photography cache: a carnival of eye candy from a nearby supernova remnant, Cassiopeia A. The images provide the most detailed look at this glowing orb of gas and dust left over from the explosive death of a massive star centuries ago. You'll see bright pink strands of gas, orange and red flows of material from the dying star, and even a bizarre-looking bubble now dubbed the "Green Monster."

The climate emergency calls for big ideas. Author Douglas Fox (*page 34*) digs into one called enhanced rock weathering, which entails spreading crushed rock across farm fields to suck carbon dioxide from the air (and potentially raise crop yields). The venture would require a mountain of mining, however, which releases its own CO_2.

Space environmentalist Moriba Jah (*page 28*) warns that the amount of space junk orbiting our planet is rising fast, and if we don't act soon, space will become unusable, taking with it technology we've come to rely on. The answer, Jah says, is to establish a "circular economy" that promotes the "reduce, reuse and recycle" mantra followed on Earth.

Since 2010 scientists have known that early *Homo sapiens* interbred with Neandertals, and most people still carry the genetic fingerprint from this intermixing. On page 42, neuroscientist Emily L. Casanova and geneticist F. Alex Feltus write about the accumulating research that indicates Neandertal DNA doesn't just sit quietly in our genomes; it affects some brain structures and even our propensity for certain neurodevelopmental and psychological conditions. We hope reading this issue expands your mind and encourages you to explore the unknown. ⬢

Jeanna Bryner is interim editor in chief of *Scientific American.*

MARK ROSS **A NEW UNDERSTANDING OF THE CELL**

PAGE 22 Where Mark Ross (*above*) grew up in rural Connecticut, winters were often cold and dreary. "When you're an artist, it's good to have bad weather," he says. "You just stay inside and work, and you don't feel bad about not being outside." The bucolic New England landscape inspired him to paint, and he has applied his skills to a career as an illustrator. Now based in Austin, Tex., Ross has illustrated more than a dozen *Scientific American* covers on topics from atmospheric storms to time crystals to nuclear fusion. For this issue's cover and the article's opening art, he depicted the molecular blobs that have changed scientists' understanding of cell biology. With many of the subjects he visualizes, "nobody can actually see any of these things, really," he says. That gives him a lot of room for creativity when designing his captivating images.

Ross loves depicting these cutting-edge scientific subjects, but he also makes time every week to practice drawing a more classical one: the human body. "It's like working out, really," he says of his weekly figure painting. During these three-hour sessions, his focus narrows to depicting the person in front of him: "The painting feels much more alive and immediate than if you're working from a photo."

PHILIP BALL
A NEW UNDERSTANDING OF THE CELL

PAGE 22 Science writer Philip Ball sees the blobs everywhere. About a decade ago he visited a laboratory in Germany where scientists had found a strange clumping mechanism in worm embryo cells. These so-called biomolecular condensates have turned out to be important for just about every aspect of cellular function. "It's kind of extraordinary," Ball says. "Every week it feels to me that I'm looking at papers [where] there's a new kind of role for condensates."

In his cover story, Ball explores how these mysterious and vital blobs are rewriting our narrative about how cells work. Traditionally the cell has been described like a machine, but Ball has suspected this was too simplistic since his days getting his Ph.D. in condensed matter physics. He'd had "this feeling that there's more going on in cells than we acknowledge."

After thoroughly enjoying writing his thesis ("which is weird, because most people hate that," he says), Ball decided to pursue a career as a science writer and has now authored 30 books. His most recent one, *How Life Works,* explores this new, rich vision of biology's inner workings. "I do really think we need to get away from this metaphor of the machine when we're talking about the cell," he says. "There is no machine we have ever built that works in the way these entities seem to."

MORIBA JAH
HOW TO RECYCLE SPACE JUNK

PAGE 28 After Moriba Jah enlisted in the U.S. Air Force, he was stationed in Montana guarding nuclear weapons. "That's when I got exposed to the darkest night I had ever [seen] in my life," he says. "The sky's just jam-packed with stars," he adds—and with satellites. Routinely seeing satellites with the naked eye inspired him to become a space scientist tracking human-made objects in orbit. Then, after having a "deep spiritual experience" while on a trip in 2015 with his son in Denali, Alaska, he felt called to focus his research on making humans' use of space sustainable. "Orbital space around Earth is part of Earth," he says. "Earth, land, ocean, space—they're all interconnected."

During the past century people have treated space—like land and oceans before it—as a dumping ground. In his feature article, Jah argues for the creation of a circular space economy. "Everything we launch is a single-use satellite, and it's as bad as a single-use plastic," he says. "When [the machines] die, they stay in orbit for many years."

In the past decade this problem has escalated, he notes, and it is becoming more and more common for pieces of space junk to fall back to Earth, threatening lives. "Until we get into using reusable and recyclable satellites in orbit," Jah says, "we're going to be facing increasingly challenging times ahead."

ZANE WOLF **GRAPHIC SCIENCE**

PAGE 88 In college, Zane Wolf's career plan was to say yes to everything that sounded fun. That's how they ended up working in five labs, studying abroad in Australia and doing fieldwork in Antarctica. Wolf studied both biology and applied physics, and for their Ph.D. they married the two fields by developing soft robotic systems that mimic how fish swim. "I love being guided by curiosity, digging into the data, finding out what the story is—and then sharing what I learned," Wolf says.

This far-reaching, restless curiosity has guided them to data visualization and a graphics internship with *Scientific American.* For this issue's Graphic Science, written by Clara Moskowitz, Wolf charted the growth of one of humanity's coolest clubs: people who have been to space. This is "one of the most exclusive groups of humans on planet Earth," they say. Wolf once dreamed of being an astronaut (as a kid, they went to space camp "not once but at least three times"). They designed the spread with subtle visual metaphors in mind. "There are mountains, there are clouds, there are rocket-launch trails," Wolf says. "That's really fun, making the data kind of resemble the topic."

Mark Ross

October 2024

TIME IN MINDFULNESS

In "Ultrasound Meditation" [Advances], Lucy Tu reports on a study by Brian Lord of the University of Arizona and his colleagues on using brain stimulation to enhance mindfulness, published in *Frontiers in Human Neuroscience.* The article is thought-provoking. The pioneering work at the University of Wisconsin–Madison and elsewhere using functional magnetic resonance imaging and other techniques to try to elucidate the neurophysiological correlates of deep meditation experience has been invaluable. Now Lord and his group are adding targeted ultrasound stimulation of the brain's default mode network (DMN) to the tools of potential value in this endeavor.

Most practitioners of deep meditative practices welcome these studies. But a word of caution is in order for those who, like the study authors and Tu, use descriptions of "subjective effects" of deep meditative states. Personal, even "scientific," bias can creep in. Among the subjective effects of the ultrasound stimulation that were cited in the article, I was most concerned with the phrase "distorted sense of time" (which reflected language used in the study). The somewhat common experience of the "nonlinearity" of time by seasoned meditators is certainly different from the day-to-day experience in the relative world in which we live. But which of those senses of time is "real," and which is "distorted"? If it turns out, as some suspect, that spacetime itself is in fact subject to the laws of quantum physics, perhaps "alternative" rather than "distorted" might be a better description.

THOMAS LONG *SCOTTSDALE, ARIZ.*

LIFE IS A BAG

As a longtime student and practitioner of pathology, I found Bethany Brookshire's essay "The Human Body Is Made of Bags" [Forum; June 2024] an amusing and appealing approach to anatomy. To take her analogy further, every anatomical "bag," from the smallest vesicle to the largest exterior surface, has openings and doors. It is at these openings that most, if not all, life processes are enabled.

On a macroscale, mouths, noses, pores, eye lenses, anuses, and so on are where all the interactions we have with our outside world occur. On an organ level, these openings enable the exchange of nutrients, gases, toxins, electrolytes, and thus everything we consume and excrete. Microscopically, cells, vesicles, and all variety of enclosures have openings, and these are usually controlled transporters. Ultimately function follows form at all levels.

JAMES EASTMAN *MADISON, WIS.*

PATTERNS ALL AROUND YOU

"Cosmic Pareidolia," by Phil Plait [The Universe], emphasizes that humans' tendency to interpret random visual patterns as something familiar often results in our seeing faces in particular. But such phenomena are not limited to faces or even to sight. I have a tile on my bathroom floor that shows a very convincing deer's head when viewed from one angle and the head, leg and foot of a crocodile from another. A gentle breeze in the trees or other quiet background sounds may be whispered voices that can't quite be understood or music that seems familiar.

JOHN RUSS *VIA E-MAIL*

GOLDEN TOURING KEY

"How Many Routes," by Heinrich Hemme [Advances; July/August 2024], presents Henry Ernest Dudeney's classic traveling-salesman puzzle from 1917. The "golden key" to solving the puzzle is typically ridiculously obvious, but just try finding it! Here we need only sketch in those road segments that must be traveled for all possible paths, namely, those segments attached to cities connected only by two roads. That golden key not only quickly gives us the answer (one path) but also provides the fun of constructing that path out of the mishmash of roads.

Years ago a friend asked me about a variation of the "knight's tour" problem, in which a chess knight begins on a square of its choosing and hops through all the remaining squares without repeating a square. Would that task be possible on a rectangle smaller than the standard 8×8 chess board? Given the knight's odd move, it was not obvious that a tour would be possible on any such rectangle. A slightly tarnished version of the above golden key, requiring additional work, showed a solution for 4×5 and 3×4 rectangles. There was no solution for some of the others.

DAVE E. MATSON *PASADENA, CALIF.*

COLD COMFORT

"Taking the Plunge," by Jesse Greenspan [Advances; June 2024], reports on research on the perceived benefits of cold-water swimming. For those who, like myself, consider swimming in frigid water a near-death experience, the humble cold shower provides an interesting alternative.

Cold showers are a form of hormesis, a phenomenon in which a stress that is harmful at high doses has a beneficial effect at low doses. As with cold-water swimming, data showing the benefits of cold showers are weak, but the feel-good

"A word of caution is in order for those who use descriptions of 'subjective effects' of deep meditative states. Personal bias can creep in."
—THOMAS LONG *SCOTTSDALE, ARIZ.*

and energizing dimensions are widely acknowledged. And one can at least minimize temperature shock by slowly adjusting the heat of the water. Maybe most important, the technique is available at home to most everyone 24/7.
RICHIE LOCASSO *HEMET, CALIF.*

THE GREATEST BUZZ

I enjoyed reading "Keeping Time" [Advances; June 2024], Meghan Bartels's piece on the emergence of two periodical cicadas, the 13-year Brood XIX and the 17-year Brood XIII, in the spring of 2024.

Here in the western suburbs of Chicago, the cicada party would begin slowly each morning with the distant "*Star Trek* phaser" drone of the 13-year insects and some local individual buzzes of the 17-year ones. Within hours any favored tree at the site was a rock-concert cacophony of sound that rose and fell as thousands of individuals sang in unison.
LORINDA GUENTHER-WRIGHT *CHICAGO*

CLARIFICATION

"Hypochondria's Serious Toll," by Joanne Silberner [December 2024], referred to the same condition as both "somatic symptom disorder" and "somatic system disorder." These terms are used synonymously, but somatic symptom disorder is the official diagnosis in the latest edition of the *Diagnostic and Statistical Manual of Mental Disorders.*

ERRATA

In "Fate of the Hybrid Chickadees," by Rebecca Heisman, the first photograph of a chickadee should have been credited to Teresa Kopec/Getty Images, and the last photograph of one should have been credited to GeoStills/Alamy Stock Photo.

"Buried at Sea," by Jaime B. Palter [December 2024], should have said that early results from the field trial of marine carbon dioxide removal in Halifax Harbor off Nova Scotia suggest that the trial moved additional carbon from the atmosphere into the ocean.

In "When Horse Became Steed," by William T. Taylor [December 2024], an image caption incorrectly described the location of Novoil'inovskiy. It is in Kazakhstan.

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ADVANCES

BIOLOGY

Brain Endurance

Misfolded proteins may preserve brains for millennia

THE BRAIN IS a particularly perishable organ. Within minutes of losing its supply of blood and oxygen, the delicate neurological machinery begins to suffer irreversible damage. The brain is the most energy-greedy part of our body, and in the hours after death, its enzymes start to devour it from within. As cellular membranes rupture, the brain liquefies. Within days microbes consume the remnants in the stinky process of putrefaction. In a few years, the skull becomes just an empty cavity.

In some cases, however, brains outlast all other soft tissues and remain intact for hundreds or thousands of years. Archaeologists have been mystified by naturally preserved brains discovered in ancient graveyards, tombs, mass graves and even shipwrecks. In a recent study, researchers at the University of Oxford surveyed scientific literature spanning centuries and counted more than 4,400 cases of preserved brains that were up to 12,000 years old.

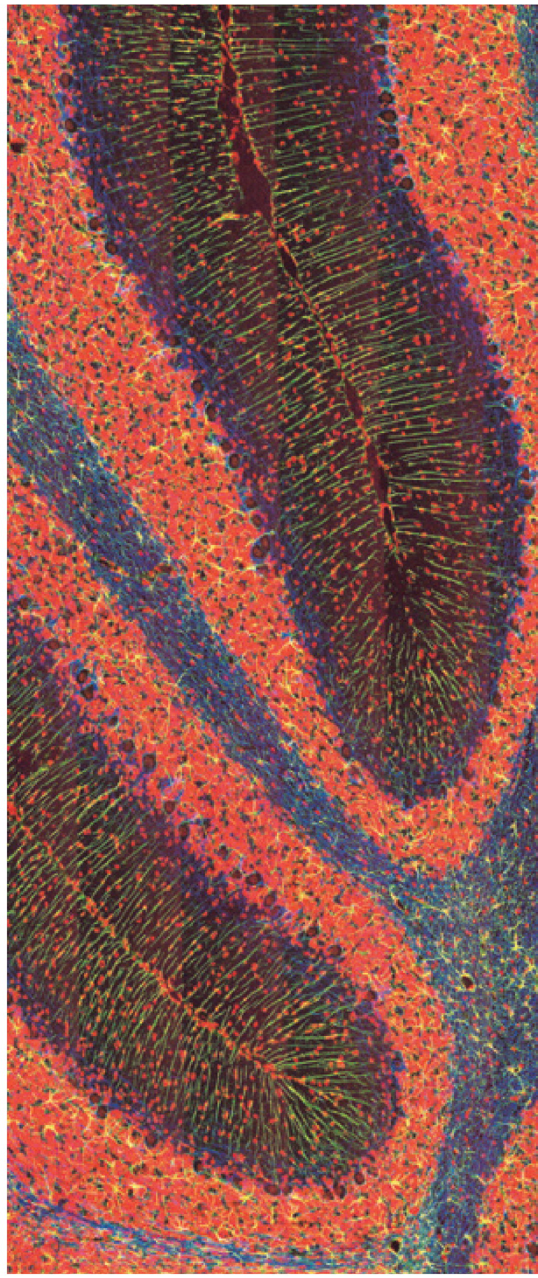
"The brain just decays super quickly, and it's really weird that we find it preserved," says Oxford's Alexandra Morton-Hayward, lead author of the study. "My overarching question is: Why on Earth is this possible? Why is it happening in the brain and no other organ?"

Such unusual preservation appears to involve the "misfolding" of proteins—cellular building blocks—and bears intriguing similarities to the pathologies that cause some neurodegenerative conditions. As every biology student learns, proteins are chains of amino acid molecules strung together like beads on a necklace. Each protein has a unique sequence of amino acids—there are 20 common types in the human body—that determines how it folds into its proper three-dimensional structure. But disturbances in the cellular environment can make folding go awry. The misfolding and clumping of brain proteins is the underlying cause of dozens of neurodegenerative disorders, including Alzheimer's disease, Parkinson's disease, amyotrophic lateral sclerosis and the cattle illness bovine spongiform encephalopathy, also called mad cow disease. Now scientists are discovering that some misfolded proteins can form clumps after death—and that these clumps can persist for hundreds or thousands of years.

Only in recent years have scientists begun to seriously investigate these bizarre cases. A big breakthrough occurred in 2008, when archaeologists discovered the 2,500-year-old skull of a man who had been hanged, decapitated and dumped into an irrigation channel in Heslington, England. All other soft tissues had long since vanished, but investigators were stunned to find that the skull still contained a shrunken brain. Analysis led by a team of University College London neuroscientists concluded the brain was preserved by the aggregation of proteins.

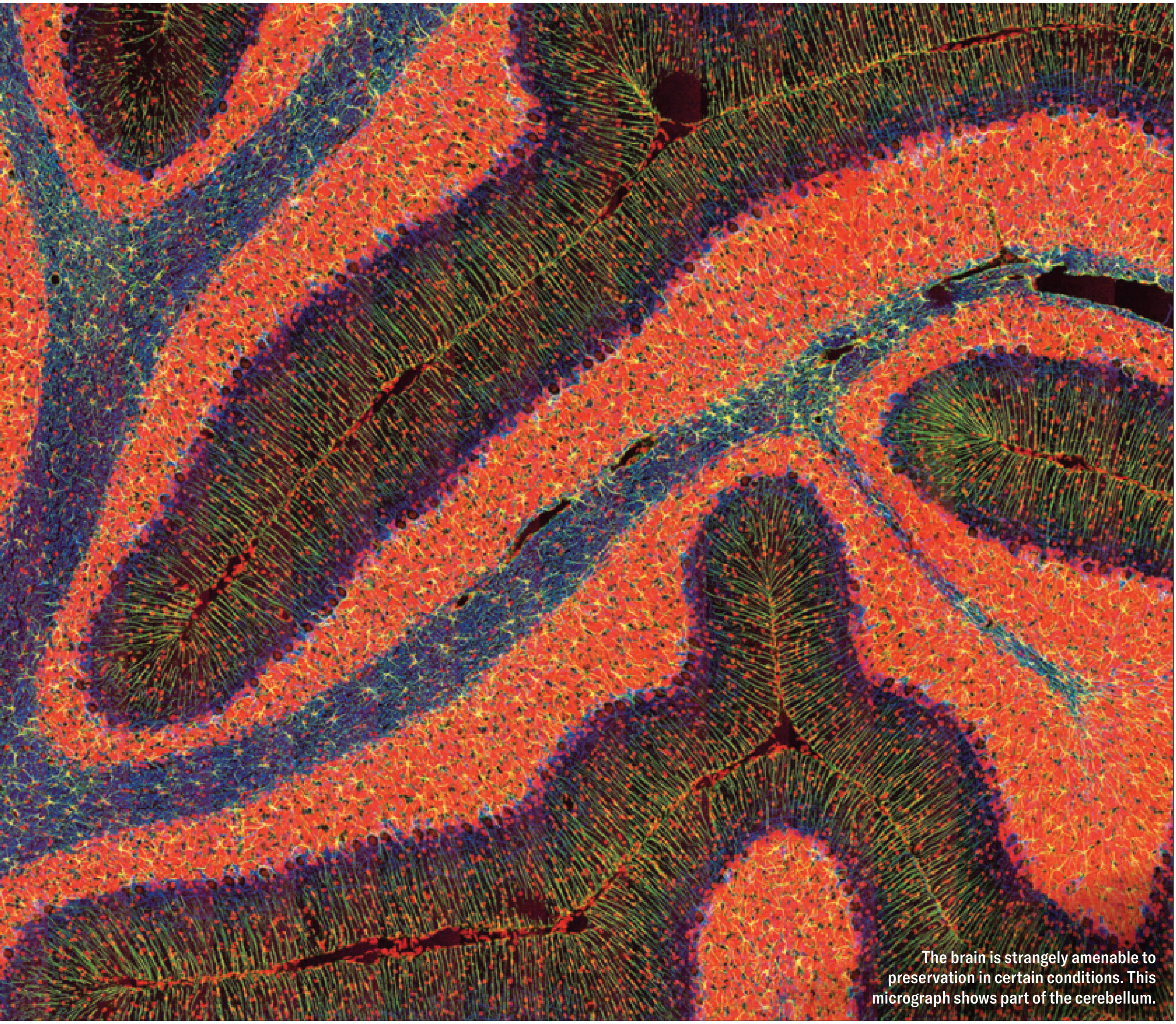
In certain brain diseases, a misfolded version of a protein becomes its most thermodynamically stable state, often making the aggregations irreversible. F. Ulrich Hartl, a leading researcher of protein-folding diseases at the Max Planck Institute of Biochemistry in Martinsried, Germany, says he would not be surprised if a similar mechanism lay behind ancient brain preservation. "The question of interest for me is: Does this reflect, in any way, what is going on during neurodegeneration?"

The Heslington brain's discovery stimulated new research into brain preservation. Oxford is at the epicenter of this effort, and its lead investigator is Morton-Hayward, a former mortician turned forensic anthropologist. Now a Ph.D. candidate, she has gathered the world's largest ancient brain collection to analyze more than 600 specimens up to 8,000 years old from locales such as the U.K., Belgium, Sweden, the U.S. and Peru. Employing an array of research



tools, she has identified more than 400 preserved proteins and revealed the minerals and molecules involved in preservation.

Typically preserved brains come from waterlogged, oxygen-poor burial environments such as low-lying graveyards. Human brains are composed of about 80 percent water, and the rest is divided between proteins



The brain is strangely amenable to preservation in certain conditions. This micrograph shows part of the cerebellum.

Thomas Deerinck/NCMIR/Science Source

and lipids: fatty, waxy or oily compounds that are insoluble in water. Morton-Hayward's experiments suggest the brains endure through a process called molecular cross-linking, in which brain protein remnants and degraded lipids form a spongy polymer. This process may be catalyzed by metals, especially iron. The polymer's strong covalent bonds, in which electrons are shared, and high molecular weights could make the shrunken brains extremely durable and chemically resistant—and thus able to defy decomposition for centuries. These polymers aren't the threadlike fibrils known as amyloid that characterize protein-folding conditions such as Alzheimer's and Parkinson's, Morton-Hayward says, but some aspects of brain preservation "closely parallel neurodegeneration." Both in the ancient brain tissues and in mouse-brain-decay experiments, she found evidence of oxidative damage caused by iron dysregulation, which has been implicated in brain aging and in

Continued on page 12

Continued from page 11
neurodegenerative diseases. “Maybe these processes are happening in life as we naturally age,” Morton-Hayward suggests, “and then, after death, they just carry on.”

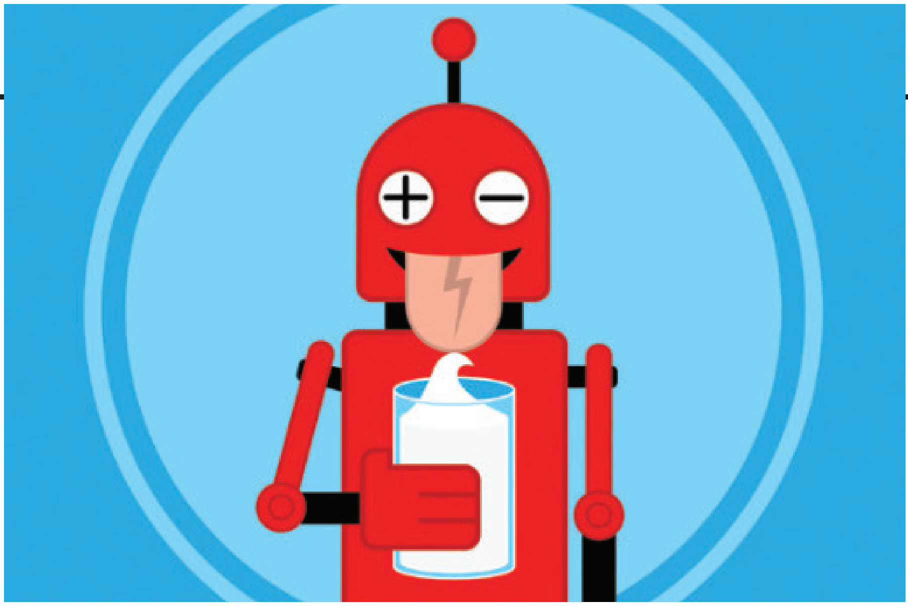
The mechanism appears distinct from how some other bodily tissues are preserved after turning to adipocere, or “grave wax,” which forms when body fats transform into a tallow-colored soaplike substance. “Adipocere forms in adipose tissue—that’s buttocks, arms, cheeks,” says Sonia O’Connor, an archaeologist and pioneering researcher of ancient brains at the University of Bradford in England. “There is no adipose tissue in the brain. It’s the wrong chemistry.”

But the brain has the right chemistry for cross-linking, thanks to its abundance of proteins and lipids. And its plasticity in life may allow its tenacity after death. About one third of all proteins are intrinsically disordered proteins (IDPs) or proteins with disordered regions, both of which can take many configurations and binding partners. Unlike normal proteins, IDPs lack a stable 3D structure and can assume many shapes, making them essential to brain plasticity but also vulnerable to misfolding.

University of South Florida biophysicist Vladimir Uversky, a leading researcher of disordered proteins, immediately suspected that IDPs played a role in the Heslington brain. When he analyzed the dataset of extracted proteins, he confirmed that the most abundant preserved proteins were marked by high levels of disorder. He hypothesizes that IDPs serve as “molecular mortar” by gluing molecules into rigid aggregates that act like “long-lasting preservatives.”

In life, we have defenses against protein misfolding, but they weaken as we age and cease entirely after death. In postmortem brains, cross-linking and aggregation can run amok, limited only by the laws of chemistry and physics.

Many preserved brains come from what Morton-Hayward calls “sites of suffering,” such as mass graves, places of violent death, and a cemetery shared by a Victorian workhouse and a mental asylum. She suspects oxidative stress during life may unleash molecular processes that continue in the grave. “In that case,” she says, “we could study aging on a much greater trajectory than just human lifespans.” *—Kermit Pattison*



Electronic Tongue An AI-based system determines drinks’ dilution, freshness and type

TECH The search for an automated way to “taste-test” products at mass-production speed and scale has stumped the food and beverage industry for decades. But in a new study, researchers used machine learning to overcome the limitations of a promising type of chemical sensor, meaning that a robotic tongue may soon assess your milk or merlot before you do.

When ions in a liquid—say, a delicious drink—touch the conductive sheet of an ion-sensitive field-effect transistor (ISFET), the electric current that flows through changes based on the liquid’s exact composition and the voltage applied. This lets scientists use ISFETs to convert chemical changes into electrical signals. The chemical makeup of any drink, and thus its taste, is influenced by contamination and freshness—which ISFETs can discern.

“The food industry has a lot of problems in terms of figuring out whether food is adulterated or has something toxic in it,” says Pennsylvania State University engineer Saptarshi Das. The first ISFETs were demonstrated more than 50 years ago, but the sensors aren’t used much commercially. The advent of graphene, an ideal conductive material, helped researchers create improved ISFET sensors that detect specific chemical ions. But a big problem remained: readings varied from sensor to sensor and with changes in conditions such as temperature or humidity.

In *Nature*, Das and his colleagues addressed this issue by marrying ISFETs with neural networks, training a machine-learning algorithm to classify drinks using the sensors’ readings. The resulting system could tell whether milk was diluted, distinguish among soda brands or coffee blends, and identify different fruit juices while judging their freshness.

During development the team tried training based on human-selected data points, but the scientists found that designations were more accurate if the algorithm was given all device measurements and chose its own data features to base decisions on. Human-chosen features were vulnerable to variations in the devices, whereas the algorithm analyzed all the data at once, finding elements that change less. “Machine learning is able to figure out more subtle differences” that humans would find hard to define, Das explains. The system managed more than 97 percent accuracy on practical tasks.

“The data are very convincing,” says University of California, San Diego, engineer Kiana Aran, who co-founded a company to commercialize graphene-based biosensors. Unlike the human tongue, which detects specific molecules, this type of ISFET system detects only chemical *changes*—“which limits it to specific, predefined chemical profiles” such as brand formulations or ranges of freshness, she says.

Next, Das and his colleagues will test larger, more diverse training datasets and more complex algorithms, as they expand the system’s reach. For example, “you can use this technology for health-care applications: blood glucose level or sweat monitoring,” Das says. “That’s going to be another area we want to explore.” *—Simon Makin*

Illustrations by Thomas Fuchs

DIET

Sweet Surprise

WWII sugar rationing boosted kids' health decades later

FOR SEVERAL YEARS after World War II ended, the British government continued to ration certain foodstuffs, including eggs, dairy products and sugar. This not only popularized resourceful recipes such as the vinegar-based "Wacky cake"; it also kept the average diet within what we now recognize as modern guidelines for daily sugar consumption. Now a study shows this restriction conferred lifelong health benefits on people who were infants during rationing.

Scientists have long wondered how sugar affects the developing body and brain. But observational studies of families who consume less or more sugar can struggle to disentangle diet's effects from those of related factors such as income or geographic location. "This type of experiment helps to remove some of that noise," says Juliana Cohen, a nutrition researcher at Merrimack College and the Harvard School of Public Health, who was not involved in the work.

The study authors used the medical database U.K. BioBank to compare disease incidence in about 60,000 people born in the years before or after sugar rationing ended in September 1953. The transition sharply altered sugar intake without affecting other dietary factors—rationing of other ingredients ended on different dates—allowing the researchers to probe the effects of reduced sugar within the developmentally crucial first 1,000 days of life.

Infants conceived in the years before sugar rationing ended had a 35 percent lower risk of diabetes and a 20 percent lower risk of hypertension in their 50s and 60s compared with those conceived after, the team reported in *Science*. For ration-era kids who ultimately did develop these conditions, onset was four and two years later, respectively. The longer a person lived under rationing, the greater the benefit they saw—but the strongest effects came while in utero and past the first six months of life, when babies begin eating solid foods.

Many mechanisms could explain the results, says lead author Tadeja Gračner, an economist at the University of Southern California. People who consume excessive sugar might gain an unhealthy amount of weight or develop diabetes during pregnancy, putting their children at risk for obesity and insulin resistance. High sugar intake could also prompt a growing fetus to express different genes to similar effect. And children raised on sugary diets may simply come to prefer sweeter foods; in a separate study, Gračner's team found that people exposed to rationing consumed less daily added sugar as adults than those who weren't.

The Centers for Disease Control and Prevention recommend that kids younger than two avoid added sugar and that everyone else keep their daily intake to less than 10 percent of their total calories. But today's American toddlers average far more (nearly six teaspoons of added sugar a day), and many pregnant people consume triple the recommended amount for adults. Cohen notes dietary change is difficult because our nutritional environment isn't set up to support it—yet any reduction helps, and there's no need to avoid sugar entirely.

"It's all about moderation," Gračner says. "A birthday cake, candy, a cookie here and there—these are all treats we need to enjoy." —*Saima S. Iqbal*

Lydia Whitmore/Getty Images

Boris Zhitkov/Getty Images

ENVIRONMENT

Carbon Scrubber

An exotic powder pulls CO_2 from the air at record speed

SCIENTISTS AND ENGINEERS are developing big machines to suck carbon dioxide out of the atmosphere, but the technology sucks up a lot of energy and money as well—as much as $1,000 per metric ton of captured CO_2. A team led by chemists at the University of California, Berkeley, has created a yellow powder that might boost this field by absorbing CO_2 much more efficiently.

Detailed projections indicate that to achieve climate targets, the world will need to remove far more CO_2 from the atmosphere than it is currently extracting. The U.S. is investing billions of dollars in startups developing direct air-capture (DAC) technology, which uses fans to blow air through alkaline materials that bond with the slightly acidic CO_2. Lye and lime powder are sometimes used in this process, as are amines—compounds typically manufactured from ammonia.

For their alternative, graduate student Zihui Zhou and professor Omar Yaghi, both at U.C. Berkeley, embedded amines in a crystalline compound with extensive surface area known as a covalent organic framework. The resulting powder, which they named COF-999, is a microscopic scaffolding of hydrocarbons held together by superstrong carbon-nitrogen and carbon-carbon bonds, such as those found in diamonds. The amines sit in the scaffolding's open spaces, ready to snag passing CO_2 molecules. When Zhou and Yaghi pumped air through a tube packed with COF-999, the powder captured CO_2 at the fastest rate ever measured, the researchers reported in *Nature*. "We were scrubbing the CO_2 out of the air entirely," Yaghi says.

Besides equipment, the biggest cost for DAC is often energy to heat the absorbent material so it releases the captured CO_2, which is collected in tanks and later injected underground or sold to industry. The powder released CO_2 when heated to 60 degrees Celsius—a much lower temperature than the more than 100 degrees C needed at current DAC plants. The team then deployed the powder again to grab additional CO_2 from the air. After more than 100 catch-and-release cycles, it showed no significant decline in capacity, according to the study.

This story was produced in partnership with the Pulitzer Center's Ocean Reporting Network.

The COF-999 compound might also compete with liquid amines used in carbon capture and storage scrubbers on refinery and power plant smokestacks, Yaghi says. It's light enough—200 grams can draw down as much CO_2 in a year as a large tree—that it could potentially be used onboard ships to strip carbon from their exhaust, too.

Companies already manufacture similar materials, metal organic frameworks, to capture CO_2 from smokestacks as well as for masks to protect against hazardous chemicals. In these crystalline structures, the superstrong bonds are formed between metal compounds rather than hydrocarbons. But Yaghi, who owns a company that produces both types of materials, says COF-999 can be more durable, water-resistant and efficient at removing CO_2 than leading metal organic frameworks. A recent *Nature Communications* study reports that another covalent organic framework based on phosphate bonds also has potential for carbon capture.

The COF-999 powder hasn't yet been tested for real-life applications, notes Jennifer Wilcox, a University of Pennsylvania chemical engineer who formerly worked on carbon removal at the U.S. Department of Energy. For example, if it restricts airflow too much when coating a filter or formed into pellets, that could increase energy consumption by fans that move the air. Such engineering properties, Wilcox says, "will ultimately dictate costs."

—Alec Luhn

Prime Detective Study probes the limits of finding prime numbers

MATHEMATICS Prime numbers have captivated mathematicians for centuries with their unpredictable and seemingly random distribution. In a groundbreaking preprint study, researchers devised a novel method that bolsters our hunt for the cagey values—but also reveals limits to our ability to detect them.

Prime numbers are divisible only by 1 and themselves. They serve as the "atoms" of mathematics, capable of decomposing other numbers into factors (like $12 = 2 \times 2 \times 3$). As numbers increase, identifying primes becomes more and more challenging. If you were asked, "How many primes are there between 1 and 1,000?" where would you begin?

The classical Sieve of Eratosthenes offers a starting point. This ancient technique systematically eliminates multiples of each prime, allowing only the primes themselves to "fall out." Mathematicians refer to the eliminated multiples as "Type I information," which can help predict how many primes are in a given range. Yet this information is limited. "Sometimes you have as good Type I information as you can possibly hope for, but you still can't find any primes," explains study co-author Kevin Ford, a mathematician at the University of Illinois at Urbana-Champaign.

Ford and University of Oxford mathematician James Maynard provide a powerful method for studying prime numbers in large ranges by precisely estimating the number of primes that must exist within them. The work combines two complementary perspectives: the Type I information of eliminated numbers (like crossing off all multiples of 2, then 3, and so on) as well as accounting for numbers that get crossed off multiple times (like how 6 appears on the lists of multiples both of 2 and of 3)—called Type II information.

Mathematicians can adjust how they weigh each type of information to get the most accurate possible count of primes in a given range. But in carefully tuning these two knobs, the paper's authors discovered there are fundamental limits: precise mathematical boundaries where no further adjustment can improve our count's accuracy, revealing deep truths about how these numbers are distributed across the number line.

The study likens the accuracy of these estimations for a set, or "strength of information," to changing the size of the mesh in a sieve: too small, and you'll catch every number; too big, and the primes will slip through. The work "answers precisely and directly what is 'sufficiently good' information to detect primes," says mathematician Kaisa Matomäki, who studies the distribution of primes at the University of Turku in Finland. Understanding the limits when designing a sieve is crucial for developing a complete theory of prime numbers, adds Princeton University mathematician Peter Sarnak, an expert in prime sieve theory: "Uncovering what one cannot achieve is fundamental."

Ford hopes this method will help researchers attack long-standing open problems. "Primes are distributed in a very, *very,* mysterious [way], so we're trying to push our understanding just a little bit." —*Max Springer*

BIOENGINEERING

Solar Critters

Plant machinery functions inside hamster cells

MORE THAN A BILLION years ago a hungry cell devoured a tiny blue-green algae. But instead of the former simply digesting the latter, the duo struck a remarkable evolutionary deal. Now scientists are trying to engineer that miracle in a laboratory.

In a recent experiment reported in the *Proceedings of the Japan Academy, Series B,* researchers transplanted that algae's photosynthesizing descendants, plant organelles called chloroplasts, into hamster cells—where they converted light into energy, staying active for at least two days.

In 2021 biologist Sachihiro Matsunaga of the University of Tokyo reported how sacoglossan sea slugs can "steal" chloroplasts from algae they eat, fueling the slugs' energy needs for weeks. His team wanted to recreate this mechanism in other animal cells.

Scientists had previously tried transferring plant chloroplasts into fungi cells, but the cells' cleanup squad destroyed foreign organelles within hours. For their attempt, Matsunaga's group harvested extra-hardy chloroplasts from a red algae that thrives in acidic volcanic hot springs and housed them in lab-cultured hamster ovary cells.

The team isolated the chloroplasts from algal cells using a centrifuge and gentle stirring. Instead of then piercing the host cells' membranes, as in earlier work, the researchers adjusted the culture medium's composition so it coaxed the animal cells into engulfing the chloroplasts like amoebas do, Matsunaga says, "mistaking them for nutrients."

The transplanted chloroplasts maintained their structure and showed successful electron transport, a crucial step in processing light, for two days before deteriorating. Previous attempts at transplanting a chloroplast into a foreign cell had worked for just a few hours. "I was impressed that they were able to get that much mileage out of it," says cell biologist Jef D. Boeke of the NYU Grossman School of Medicine.

Challenges remain: Chloroplasts need a steady supply of proteins from the cell. "Animal cells, however, don't have the necessary genes to make and transport these proteins, so chloroplasts would break down quickly without them," says Werner Kühlbrandt, a structural biologist at the Max Planck Institute of Biophysics in Frankfurt. Like Boeke, he was not involved in the new study. Next, Matsunaga's team plans to try inserting photosynthesis-maintaining genes into animal cells, aiming to make them more compatible with the transplanted chloroplasts.

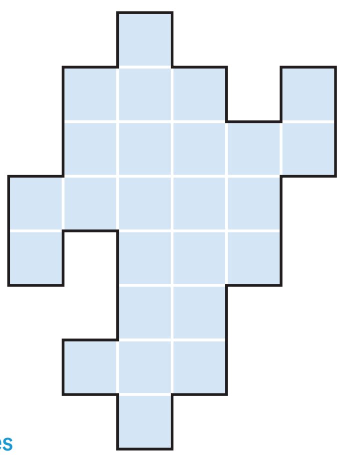
These types of transplants could someday help scientists engineer living materials, Boeke says, such as photosynthesizing fungi or bacteria that might be used on rooftops to soak up carbon dioxide from the atmosphere, or lab organoids that can grow faster using a chloroplast's extra oxygen. Solar-powered humans, of course, remain pure fantasy, Matsunaga says: "They would need a tennis court's worth of surface area covered with chloroplasts." *—Saugat Bolakhe*

MATH PUZZLE

Build a Square

BY HEINRICH HEMME

DIVIDE THIS FIGURE into three parts that can be arranged into a square. The parts must not be folded over to make their current back the front, they must not overlap, and there must not be any gaps in the square.



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

LINGUISTICS

Pain Language

The sound of "ow" transcends borders

WHAT WOULD YOU SAY if you suddenly stubbed your toe on a doorframe? Depending on how much it hurt, you might yelp in pain, unleash a stream of expletives—or utter a very specific exclamation such as "ouch" or "ow."

Many languages have an interjection word for expressing pain. In Mandarin, it's *ai-yo;* in French, it's *aïe;* and in several Australian languages, it's *yakayi.* All have sound elements that seem quite similar—and that's no coincidence, according to a recent study in the *Journal of the Acoustical Society of America*. Researchers found that pain interjections tend to contain the vowel sound "ah" (written as [a] in the International Phonetic Alphabet) and letter combinations that incorporate it, such as "ow" and "ai." These patterns may point back to the origins of human language itself.

"Across every country you see this overrepresentation of [a]" in pain interjections, says the study's senior author, Katarzyna Pisanski, who studies vocal communication at France's National Center for Scientific Research (CNRS). "It was a really strong, robust effect." Pisanski and her colleagues also found that [a] dominates the nonlinguistic, often involuntary cries of pain, called vocalizations, that people around the world utter. This commonality suggests words like "ouch" might have been shaped by the more primal sounds of pain humans evolved to make—possibly well before language or speech first developed.

Maïa Ponsonnet, the study's lead author, first noticed the similarity between *yakayi* and the French *aïe* while studying Australian languages. Obviously, "this is a very naive observation," says Ponsonnet, a linguist who also works at CNRS. "You shouldn't draw any inference from observations of just two languages." So she and her colleagues scoured dictionaries and

Spektrum der Wissenschaft

Hiraman/Getty Images

databases of 131 world languages for interjections that express pain and two other basic emotions, disgust and joy. The sample included dozens of language families from Asia, Australia, Latin America, Africa and Europe.

The researchers found striking statistical similarities in pain interjections across languages. In fact, these interjections resembled one another in different languages more than they resembled other words of the same language. This effect—which did not hold true for interjections expressing joy or disgust—was driven by one category of vowels in particular: [a]-like ones that often combine with other letters to create sounds such as "ai" and "ow."

"It doesn't often happen that a hypothesis … is tested on such a large scale and comes out so clearly," says Mark Dingemanse, a linguist at Radboud University in the Netherlands, who also studies interjections.

The pattern suggests that the words we humans use for pain are not as arbitrary as many other words. Instead they were probably shaped by some common factor. Could those similarities come from the primal, nonlinguistic sounds that seem to automatically spring from us when we get hurt? Research on this idea is scant, so Ponsonnet joined forces with Pisanski, who studies vocal communication's evolution in mammals, to conduct another experiment. The researchers recruited 166 English, Japanese, Spanish, Turkish and Mandarin speakers to produce the sounds they would make if they were experiencing pain, disgust or joy.

This time the team found that for each emotion, vocalizations contained similar vowel sounds across those five languages. For disgust, the most common sound was [ə] (pronounced like "uh"); for joy, it was [i] (pronounced like "ee"); and for pain, it was the now familiar [a].

The fact that [a] was overrepresented in both primal vocalizations and interjections for pain suggests these two types of utterance may be related, Pisanski says. It's possible that words such as "ouch" and *yakayi* have been shaped by the involuntary sounds humans evolved to make to signal pain or distress to one another.

For disgust and joy, the results tell a different story. The vocalizations for these emotions may be similar across the planet, but their interjections are far more diverse—perhaps because these feelings carry more cultural dimensions than pain, Pisanski suggests. "Pain is pain, I think, no

Continued on page 18

Continued from page 17

matter where you're from," she says. "It's a biological experience."

Our shared biology affects many aspects of language. Researchers are continually discovering cases of symbolism, or sound iconicity, in which a word's intrinsic nature has some connection to its meaning. These cases run counter to decades of linguistic theory, which had regarded language as fundamentally arbitrary (meaning, for example, there is nothing in the structure or sound of the word "bird" that would intrinsically make someone think of an actual bird).

Yet iconicity *does* show up all over human language. Signed languages, long overlooked by many linguists, employ a lot of symbolism: in American Sign Language, a person forms "bird" by using a finger and thumb to mime a bird's beak opening and closing. And in spoken languages, the term "onomatopoeia" refers to a word that imitates a sound directly, such as "bang" or "splat." Many types of birds, such as the cuckoo and chickadee, have been given names that echo their calls.

But these connections between form and meaning can be so abstract that they're all but invisible until revealed by researchers. For example, there's the "bouba-kiki" effect, whereby people from varying cultures are more likely to associate the nonsense word "bouba" with a rounded shape and "kiki" with a spiked one.

"This is [what's] beautiful about sound iconicity and symbolism—because somehow we all have a *feeling* about this," says Aleksandra Ćwiek, a linguist at the Leibniz-Center for General Linguistics in Germany. "It's amazing to see that people kind of agree on them." For a paper also published in the *Journal of the Acoustical Society of America*, Ćwiek and her colleagues showed that people associate the trilled "R" sound with roughness and the "L" sound with smoothness.

"Finding out when unrelated languages do things in similar ways brings home our common humanity," says Dingemanse, who in 2013 found the conversational "Huh?" and similar words in other languages may be universal. "No matter how much languages differ—and that is also fascinating—they also unite us." —*Allison Parshall*

PSYCHOLOGY

Wiki-Curious

Are you a " busybody," a "hunter" or a "dancer"?

THE WEBSITE WIKIPEDIA describes curiosity as a "quality related to inquisitive thinking, such as exploration, investigation, and learning, evident in humans and other animals." But there is a lot more to this prime motivator for so much of human behavior—and Wikipedia, as the world's largest encyclopedia, is now helping social scientists deepen the definition of curiosity.

Tracing how Wikipedia searchers flit among topics and lose themselves in Wiki rabbit holes revealed three different styles of human inquisitiveness: the "busybody," the "hunter" and the "dancer."

In this lexicon, a busybody traces a zigzagging route through many often distantly related topics. A hunter, in contrast, searches with sustained focus, moving among a relatively small number of closely related articles. A dancer links together highly disparate topics to try to synthesize new ideas. "Curiosity actually works by connecting pieces of information, not just acquiring them," says University of Pennsylvania network scientist Dani Bassett, co-senior author on a recent study of these curiosity types in *Science Advances*. "It's not as if we go through the world and pick up a piece of information and put it in our pockets like a stone. Instead we gather information and connect it to stuff that we already know."

The team tracked more than 482,000 people using Wikipedia's mobile app in 50 countries or territories and 14 languages. The researchers charted these users' paths using "knowledge networks" of connected information, which depict how closely one search topic (a node in the network) is related to another. Beyond just mapping the connections, they linked curiosity styles to location-based indicators of well-being, inequality, and other measures.

In countries with higher education levels and greater gender equality, people browsed more like busybodies. In countries with lower scores on these variables, people browsed like hunters. Bassett hypothesizes that "in countries that have more structures of oppression or patriarchal forces, there may be a constraining of knowledge production that pushes people more toward this hyperfocus." The researchers also analyzed topics of interest, ranging from physics to visual arts, for busybodies compared with hunters (*graphic*). Dancer patterns, more recently confirmed, were excluded.

Princeton University psychologist Erik Nook praised the study's "dazzlingly large" scope. The authors, he says, brought together expertise from a range of fields—topology, psychology, cognitive science, affective science, clinical science, sociology and computational modeling—to reveal a "host of insights into human behavior."

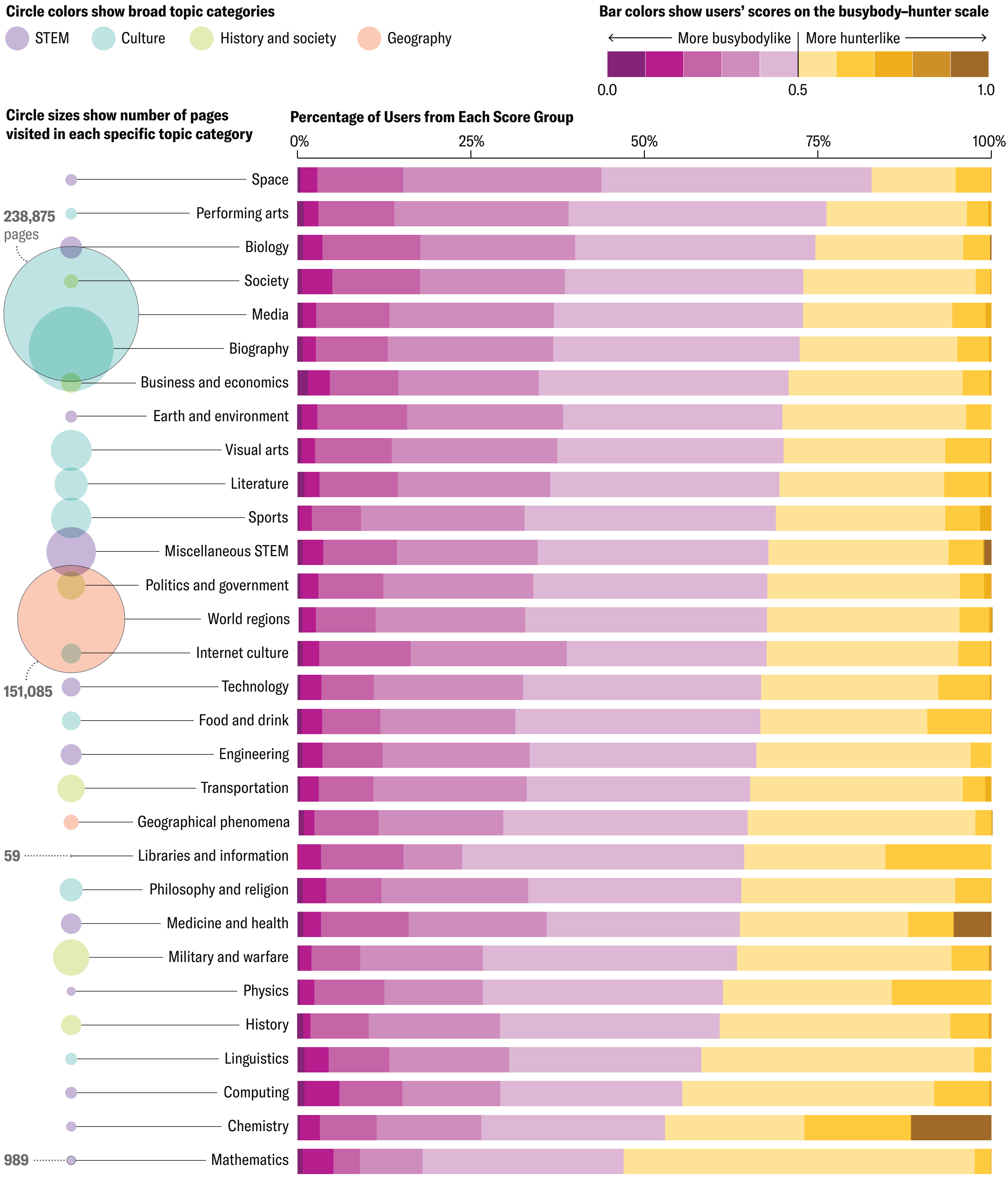
The seeds of this work were planted in 2016 when Bassett and their twin brother, Perry Zurn, a professor of philosophy at American University, noticed that plenty of academic research had examined creativity—but relatively little had gone to its requisite precursor, curiosity. Zurn emerged from a deep dive into 2,000 years of Western historical and philosophical literature with descriptions of various curiosity styles, including the three investigated in the recent paper. Wikipedia then provided the real-world test bed to confirm this busybody-hunter-dancer typology, drawn from the work of philosophical greats. Heidegger and Nietzsche could never have imagined that their work would one day influence the network science of Wiki rabbit holes. —*Gary Stix*

"Curiosity actually works by connecting pieces of information, not just acquiring them."

—DANI BASSETT *UNIVERSITY OF PENNSYLVANIA*

How Different Styles of Curiosity Drive Wikipedia Searches

Researchers explored different types of curiosity by tracking search patterns in the Wikipedia app, calculating a score for each study volunteer along a continuum of busybodylike to hunterlike behavior. Their analysis revealed patterns in overall topic popularity, as well as correlations between curiosity styles and areas of interest.



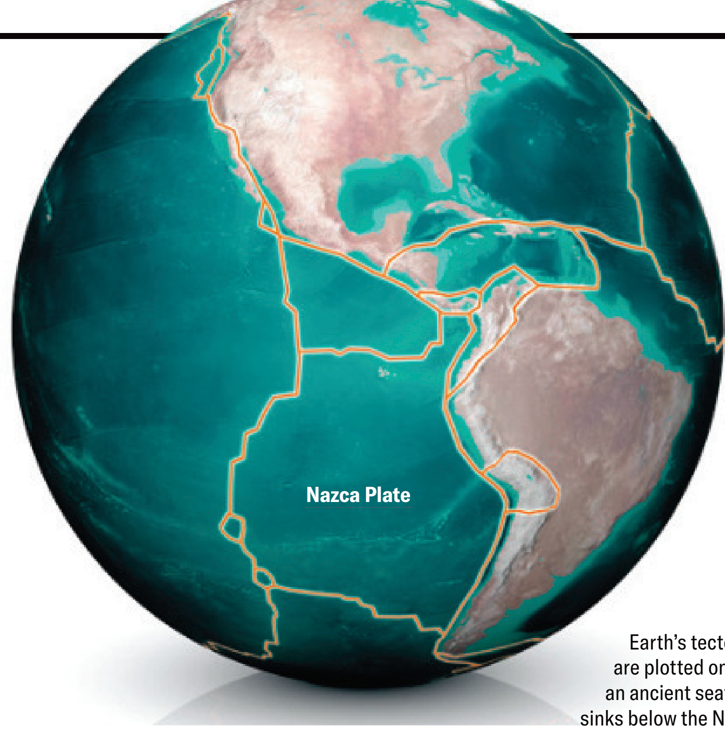
Source: "Architectural Styles of Curiosity in Global Wikipedia Mobile App Readership," by Dale Zhou et al., in *Science Advances*, Vol. 10, No. 43; October 25, 2024 (*data*)

Graphic by Amanda Montañez

GEOLOGY

Splitting the Blob

A piece of ancient seafloor is slowly diving into the planet's mantle



Earth's tectonic plates are plotted on the globe; an ancient seafloor patch sinks below the Nazca Plate.

Naeblys/Alamy Stock Photo

A SLAB OF SEAFLOOR that was around when Earth's earliest known dinosaurs emerged has been discovered underneath the Pacific Ocean. It has seemingly hovered there in a kind of mid-dive for more than 120 million years.

In addition to illuminating geological processes deep inside Earth, the cold and dense descending rock, located some 410 to 660 kilometers below the planet's surface, could explain a mysterious gap between two sections of a giant blob in the mantle layer.

A new study on the find, detailed in *Science Advances,* "provides a first present-day example of how a cold downwelling from above is breaking up a deep mantle blob," says Sanne Cottaar, a global seismologist at the University of Cambridge, who wasn't involved in the discovery.

Deep within our planet, two gargantuan, continent-size blobs of sizzling material rise from Earth's hot, liquid outer core into its rock-filled mantle layer. Scientists can't directly see these megastructures, which are hundreds of kilometers tall and thousands of kilometers wide. Instead researchers infer their existence from imaging techniques that rely on the way seismic waves travel through them. Within the blobs, seismic waves slow down, leading to these blobs' more technical name, large low-shear-velocity provinces (LLSVPs). The larger and better understood LLSVP, colloquially called the African blob, sits under the East African Rift Valley, which runs from the Red Sea to Mozambique. There two tectonic plates are slowly moving apart and may eventually split the continent.

"At the East African rift zone, we have a present-day example of how a large hot upwelling mantle plume that originates at these deep mantle blobs starts to break up a continent," Cottaar says.

Scientists aren't sure exactly how these LLSVPs formed, what they are made of or how they contribute to surface events such as volcanism. Some research suggests they are relics of the collision that created our moon. "The general idea is that mantle blobs are most likely pushed around by subducted slabs," Cottaar says, referring to the edges of oceanic plates that have descended below, or subducted, another plate. "The two main blobs are surrounded by 'graveyards' of subducted slabs."

Jingchuan Wang, a geologist at the University of Maryland, College Park, and his colleagues were interested in examining the mantle blob under the Nazca Plate in the Pacific Ocean, off the coast of South America. Past research had suggested a structural anomaly exists there that seems to split the blob in half. In the new analysis, of earthquake waves traveling deep underground, the researchers saw evidence for something cold and dense stuck in that gap.

"The most parsimonious explanation for the cold temperature and high seismic velocity is the presence of a subducted slab," Wang says. "But this area has no active subduction, and the imaged slab has already detached from the surface. Therefore, we believe we are observing an ancient slab."

Wang's team describes two possible scenarios for how this ancient seafloor ended up wedged in the middle of the Pacific mantle blob. In one, some 250 million years ago a broken-off edge of seafloor began to fall between the predecessor of the Nazca Plate and the part of the supercontinent Gondwana that later became South America. That broken plate part, which functioned as the seafloor during the early Mesozoic era, would have sunk below those two plates, whose boundary now forms the fastest-widening oceanic ridge in the world, called the East Pacific Rise. Alternatively, the descending slab might have dipped under the Nazca Plate's predecessor, Wang says, in a bout of ancient tectonic reshuffling.

Regardless of how it got there, part of that seafloor is very slowly creeping downward at a pace of about 0.5 to one centimeter a year—nearly half the rate at which a similar object would sink if it were lodged just below this zone in the mantle. The thickness of the slab and the viscosity (or gumminess) of this region of the mantle, Wang says, could explain the slow sinking speed.

"Our findings help to link the plate tectonic history of the past 250 million years to present-day mantle structures," Wang says, "providing clues about Earth's complex past, in particular what was happening in the subsurface, which often leaves no discernible geological fingerprints on the surface." —*Jeanna Bryner*

O. Usykov Institute for Radiophysics and Electronics, Kharkiv

The institute has been created as a center for theoretical studies, laboratory research, and mass production design. The generation, transmission, and reception of electromagnetic waves are comprehensively studied here.Ukraine's only microwave cryogenic complex is located in the institute, which is used for research on magnetic nanoparticles.

In March-April 2022, due to the Russian invasion and the battles on the northern outskirts of Kharkiv, the buildings of the institute were damaged by shelling. The photo shows employees on the territory of the institute, who, regardless of the war, stay in the country and continue their work.

Photographer: Valentyn Kuzan

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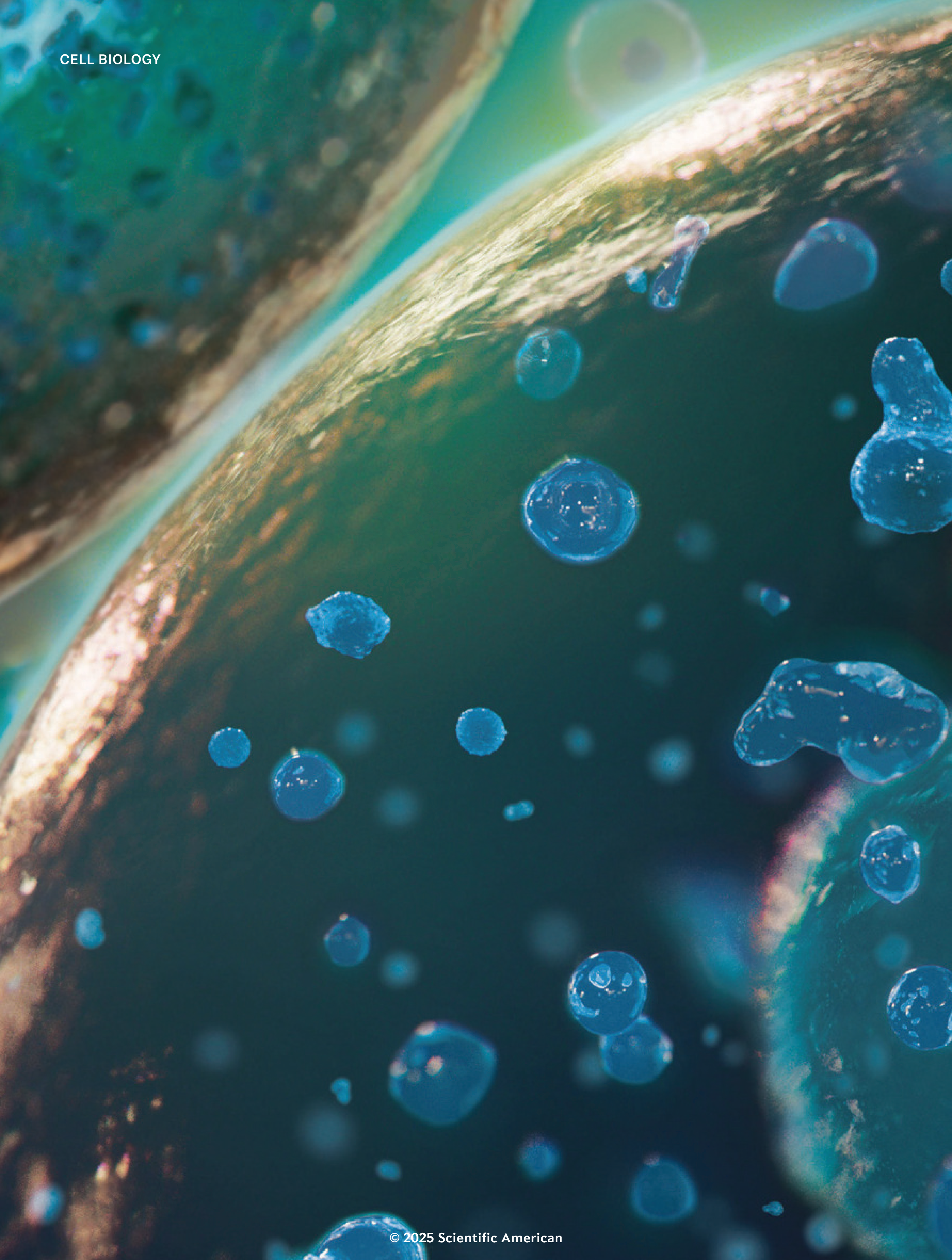

A NEW UNDERSTANDING OF THE CELL

Gloppy specks called biomolecular condensates are rewriting the story of how life works

BY PHILIP BALL

ILLUSTRATION BY MARK ROSS

NO ONE SAW THE BLOB TAKEOVER COMING. In 2009 a team of biophysicists led by Anthony A. Hyman of the Max Planck Institute of Molecular Cell Biology and Genetics in Dresden, Germany, were studying specklelike structures called P granules in the single-celled embryo of a tiny, soil-dwelling worm. These specks were known to accumulate only at one end of the cell, making it lopsided so that, when it divides, the two daughter cells are different. The researchers wanted to know how that uneven distribution of P granules arises.

They discovered that these blobs, made from protein and RNA, were condensing on one side of the cell like raindrops in moist air, and dissolving again on the other side. In other words, the molecular components of the granules were undergoing phase transitions like those that switch a substance between liquid and gas.

That was a weird thing to be happening in cell biology. But at first it seemed to many researchers little more than a quirk and didn't excite much attention. Then these little blobs—now called biomolecular condensates—began popping up just about anywhere researchers looked in the cell, doing a myriad of vital tasks.

Biologists had long believed that bringing order and organization to the chaos of molecules inside a cell depended on membrane-bound compartments called organelles, such as the mitochondria. But condensates, it turns out, offer "order for free" without the need for membranes. They provide an easy, general-purpose organization that cells can turn on or off. This arrangement permits many of the things on which life depends, explains biophysicist Petra Schwille of the Max Planck Institute of Biochemistry in Martinsried, Germany.

These little blobs inside living cells now appear to feature across all domains of the living world and are "connected to just about every aspect of cellular function," says biophysical engineer Cliff Brangwynne, who was part of the 2009 Dresden team and now runs his own lab at Princeton University. They protect cells from dangerously high or low temperatures; they repair DNA damage; they control the way DNA gets turned into crucial proteins. And when they go bad, they may trigger diseases.

Biomolecular condensates now seem to be a key part of how life gets its countless molecular components to coordinate and cooperate, to form committees that make the group decisions on which our very existence depends. "The ultimate problem in cell biology is not how a few puzzle pieces fit together," Brangwynne says, "but how collections of billions of them give rise to emergent, dynamic structures on larger scales."

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These ubiquitous specks have "completely taken over cell biology," says biophysicist Simon Alberti of the Technical University of Dresden. The challenge now is to understand how they form, what they do—and perhaps how to control them to devise new medical therapies and cures.

INITIALLY RESEARCHERS studying condensates thought they formed by coalescing as one liquid phase became insoluble in another—like vinegar droplets in the oil of salad dressing. But condensates aren't always simply phase-separated liquids.

In 2012 biophysicist Michael Rosen of the University of Texas Southwestern Medical Center in Dallas and his coworkers showed that various proteins and RNA molecules could phase-separate from a solution into dense liquid droplets, which then congealed into viscoelastic substances. They seem to span the range from gloppy liquids such as mucus to almost solidlike gels such as Jell-O. Or, as biophysicist Rohit Pappu of Washington University in St. Louis describes it, "all condensates are Silly Putty."

The umbrella term "biomolecular condensates," proposed by Hyman, Rosen and their colleagues in 2017, distances these ubiquitous blobs from the early notion that they are all liquids.

Condensates can look messy compared with the precise molecular unions that biochemists and molecular biologists are used to studying. They are not a static form but molecular meeting places, often loose collections of several different components, some of which can move into or out of the blobs. Some of these ingredients, called scaffold molecules, are essential to the fabric, sticking together into gel-like networks. Others, sometimes referred to as client molecules, merely hang out in the network. Both types, however, seem able to come and go from the condensate without it falling apart.

Typically the gels contain proteins and RNA molecules. The archetypal image of a protein is an enzyme, made from a chain of amino acids tightly folded into a globule. But many of the proteins in condensates have parts that are more open and floppy (like cooked spaghetti), or what biochemists call intrinsically disordered regions.

Such condensate-forming proteins often appear to have sticky patches, for example, where the chains carry electrical charges that can attract one another, joined together by disordered and flexible spacer segments. Unlike the conventional view that proteins, like enzymes, bind other molecules tightly and very selectively, the interactions of intrinsically disordered proteins can be rather weak and promiscuous: they aren't too choosy when it comes to what they bind.

Another ingredient of many condensates is RNA molecules, which are also long chains studded with electrical charges. RNA was long considered to serve mostly as an intermediary that carries information from a gene to the machinery of the ribosome, which translates it into the amino acid sequence of a protein's chain. But condensate-forming RNAs are generally members of a different family: noncoding RNAs, which are not mere messengers for making proteins but are ends in themselves.

Some of the proteins in condensates, meanwhile, belong to a family whose job seems to be to bind RNAs. By tuning protein and RNA sequences and structures to alter their binding propensities, biology has dials for altering the functions of condensates or the conditions under which they form.

Proteins, for example, might be switched into condensate-forming mode when enzymes decorate them with other chemical groups such as electrically charged phosphates, altering their shape and stickiness. Or these blobs might be summoned when a cell starts synthesizing the constituent RNA. That seems to be what happens, for example, when our own cells make a noncoding RNA called NEAT1, the scaffold for condensates called paraspeckles that play a role in regulating genes.

WEIRDLY, SCIENTISTS HAVE had evidence of the existence of condensates for as long as they have known about living cells—they just didn't know what to make of them. Way back in 1830 mysterious specks were seen by early microscopists inside the cell nucleus. Then called nucleoli, they were later found to be where the ribosome is made. But it wasn't until 2011 that Brangwynne, Hyman and veteran cell biologist Tim Mitchison of Harvard Medical School clarified what nucleoli actually are: phase-separated liquidlike droplets.

These particular blobs have many jobs. It seems they help to keep all the many steps of ribosome assembly—made of many proteins along with pieces of RNA—under control. Brangwynne and others have shown that the liquidlike nucleoli (a type of condensate) are subdivided into several concentric layers with different compositions, like the shell, white and yolk of an egg. "This layered condensate allows for spatial segregation of the different processing steps," he explains.

Besides the nucleoli, condensates are associated with other long-recognized compartments and organelles of the cell. One of them is called the Golgi: a set of stacked ribbonlike lipid membranes near the nucleus that acts as a kind of sorting hub for proteins and other molecules. Yiyun Zhang and Joachim Seeman of University of Texas Southwestern Medical Center in Dallas have shown that, when cells are stressed, these ribbons are maintained or repaired by a condensate formed from a protein called GM130.

The protein creates a matrix on a Golgi membrane and then gathers RNA and RNA-binding proteins into a liquid phase that helps to glue the membranes into a stack. Under stress conditions, however, the protein and RNA dissociate, the condensate comes apart, and the ribbon starts to disintegrate. Then the freed-up GM130 gathers with RNA into condensate "stress granules," which store it ready for gluing the membranes back together when the stress has passed.

That's just one example of how condensates help to sustain cells through difficult times. One common stressor is heat, which can cause folded proteins to "denature," or unravel. Many cells make heat-shock proteins when they get uncomfortably warm, which can act as molecular chaperones that guide denatured proteins back to their folded state. That's important not just so the proteins work properly but so unfolded proteins do not stick together in a gloppy mess.

But according to biochemist D. Allan Drummond of the University of Chicago, there was always something a bit screwy about this picture. It implies that if cells are becoming too hot and need to make heat-shock proteins, they can sense it only if the damage has already happened. "It just doesn't smell right," he says.

Instead Drummond suspects the way cells sense temperature—and other forms of stress—is by condensate formation. In 2017 he and his coworkers found that stress granules, blobs that appear in yeast cells, contain condensates made of an RNA-binding protein called Pab1. When this protein gets bound up in a condensate, it loses most of its ability to bind messenger RNA molecules that encode chaperone proteins needed to protect against heat shock.

When the researchers introduced mutations into the gene that encodes Pab1, they could alter the resulting protein's propensity to form condensates so that cells with the mutation fared poorly when warmed. Thus, Drummond thinks condensate formation—a phase transition that happens abruptly at a particular threshold (in temperature, say)—is itself the stress sensor that alerts the cell to the problem and provokes a response. "You add condensates into the picture, and you utterly rewire your thinking about it," he says.

Another common threat to cells is DNA damage, caused by exposure to ultraviolet light or environmental toxins, for example. Alberti's group has found that condensates can act as a superglue to hold damaged DNA strands together while enzymes repair them.

DNA repair has long been known to involve a protein called PARP1, and in early 2024 Alberti's team reported that this molecule travels along DNA strands until it finds a break, whereupon it aggregates with the DNA into a condensate, shielding the damage from the rest of the nucleus. "The glue is very solid," Alberti says. A protein called FUS then gets incorporated into the blob of glue and softens it so that other enzymes can work within the condensate to join the ends of the strand back together. Because DNA damage can be fatal to cells, drugs that target PARP1 in cancer cells and arrest DNA repair by fixing the glue in its "solid" form might kill them.

Organizing complex biochemical processes and responses to stress are two common functions of condensates. Pappu, his colleague Yifan Dai and their coworkers have recently found another: Condensates can act as catalysts for biochemical reactions, even if their component proteins do not. This is because condensates create an interface between two phases, which sets up a gradient in concentrations—of ions for example, creating an electric field that can trigger reactions. The researchers have demonstrated condensate-induced catalysis of a wide range of biochemical reactions, including those involving hydrolysis (in which water splits other molecules apart).

Condensates may also play a part in one of the most important processes in biology: how genes are regulated to determine whether or not they generate their corresponding proteins. In complex organisms such as humans, the initial process of transcription—where the gene in DNA is read to make the mRNA molecule that templates the protein—is a bafflingly complicated affair. It involves many players: DNA regions outside the gene itself such as enhancers (which are often on rather distant parts of the strand), proteins called transcriptions factors that bind to DNA, RNA-making enzymes, and more.

How all these components get together and reach a group decision to regulate transcription is still unclear. "When I was transitioning from physics into biology," Pappu says, "I would sit there [at conferences] listening to these gene-regulation talks—this activates this, and this recruits

Condensates now seem to be a key part of how life gets its countless molecular components to coordinate.

What Goes into a Blob?

Biomolecular condensates, long overlooked in cell biology, are now recognized as essential for cellular function. These blobs protect cells, repair DNA and regulate protein production. And when they malfunction, they might contribute to diseases such as cancer and Alzheimer's. Condensates may form through phase transitions, reshaping our understanding of cell biology and driving new research into their role in health and disease.

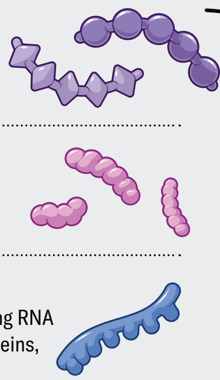
HOW DO CONDENSATES FORM?

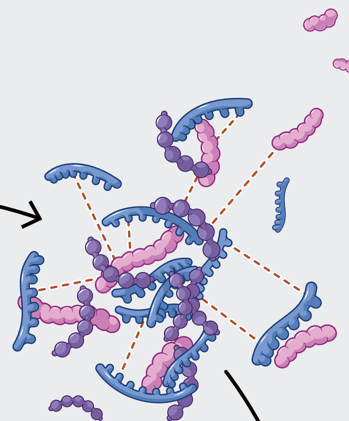
Condensates are small, membraneless clusters of molecules, primarily proteins and RNA. They form within cells via a process called phase separation—the same process behind oil separating from water. Under different conditions, condensates form to carry out particular functions in a cell. They are often thought to consist of three main components:

Scaffold Proteins
Proteins that form the structure of the condensate.

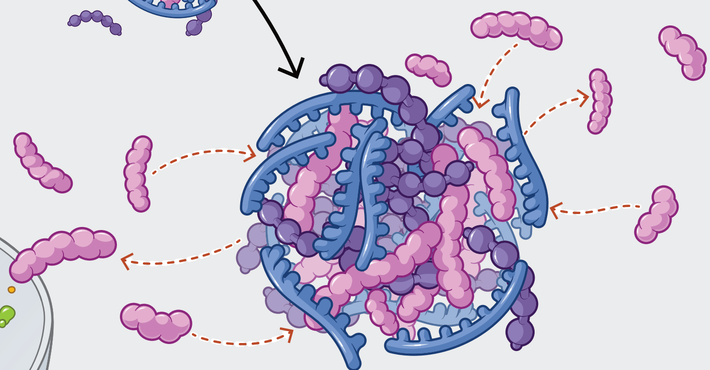
Client Proteins
Components of condensates that are not essential for the structure.

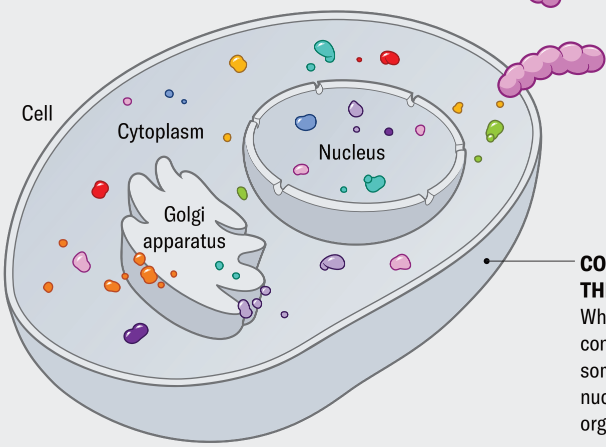
RNA
These nucleic acids, often including RNA molecules that do not encode proteins, are found in most condensates.





CONDENSATES ARE NOT MEMBRANE-BOUND
As more proteins bind together, this further allows more molecules to bind and join the condensate. The condensate provides its own chemical environment, allowing different reactions and processes to occur in isolation from what happens in the surrounding cell space.

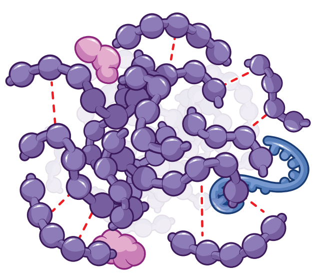




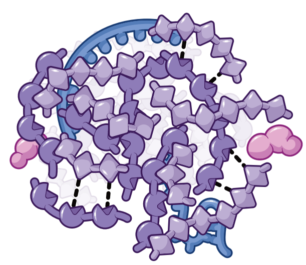
CONDENSATES FORM SPONTANEOUSLY WHEN THRESHOLD CONDITIONS ARE MET
Whether condensates are present may depend on specific conditions being met, such as temperature in the case of some stress granules. They have been observed within the nucleus, the cytoplasm, and within or around other cell organelles, such as the Golgi apparatus.

DIFFERENT FORMS FOR DIFFERENT FUNCTIONS

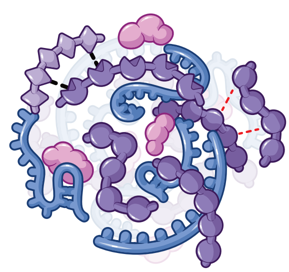
Condensates vary greatly in the molecules and types of binding that cause them to form. How they come together depends on the specific conditions and functions required. Some even have internal structure, such as a dense core and fluid shell or blobs within blobs (*not shown*). Understanding how the components bind may have implications for understanding the processes behind diseases such as Alzheimer's and cancer.



WEAK FLEXIBLE BINDING
Weak transient interactions (*red*) are useful for processes like signaling and regulation, and are fundamental for forming condensates.



SPECIFIC AND STABLE BINDING
Some condensates appear to form through highly selective and strong bonds (*black*)—such as hydrogen bonds—between their components.



COMBINATION
Some condensates may arise from mixtures of weak, promiscuous interactions and more stable and selective binding.

Graphic by Now Medical Studios

that—and I was always thinking: 'Are these molecules making cell phone calls to one another? What the devil's going on?' "

It seems that condensatelike aggregates may be what bring these components together within the tangle of DNA in the cell nucleus. The DNA strand might itself act as a seed for such droplets, like the atmospheric dust particles that seed the condensation of cloud droplets. This blob can then suck in the distant enhancer regions on loops of DNA while gathering all the other molecules needed and stopping them from drifting off.

Molecular gatherings during transcription are considerably smaller affairs than those in many other condensates, and it is hard to get a clear view of them inside the nuclei of living cells. So there's still debate about whether such "transcriptional hubs" are true liquid droplets and whether condensate formation is an essential part of the process or a side effect. Another possibility, Drummond says, is that all these molecules, once brought together into the same space, fit together into a more orderly complex to initiate transcription, but their congregation also generates condensates.

There's much to be unraveled. "I tell people that all I know is that these [transcriptional] proteins really want to phase-separate," Brangwynne says. "I just don't see another plausible model. Phase separation is the most parsimonious explanation."

PROTEINS AGGREGATING into dense blobs seems to be an essential aspect of how life works. But there's a dark side to this process.

Tangled clumps of protein have long been linked to neurodegenerative conditions such as Parkinson's and Alzheimer's. These solidlike knots, called amyloids, can be toxic to cells and kill off neural tissue. Some researchers suspect that such problematic protein aggregates might arise from improper control of ubiquitous, ephemeral condensates, for example, because of gene mutations affecting the constituent proteins in ways that make them apt to congeal into long-lived solid lumps.

At first the mantra among researchers was "liquid good, solid bad"—but that's clearly too simplistic because healthy condensates have a range of material properties that can include solidlike. What really distinguishes "good" from "bad" condensates is now one of the pressing questions for the field.

The possible connection between condensates and pathological amyloids is being explored in the search for treatments for neurodegeneration. It's possible that antisense oligonucleotides—short segments of nucleic acids that can bind to RNA—might be used to inhibit the aggregation of proteins associated with these conditions. They are also being explored for disabling condensate-forming RNA molecules.

Similarly, the importance of condensates such as paraspeckles in gene regulation means that their dysregulation might lead to all manner of diseases, including cancers. There is now an emerging field of condensate therapeutics being pursued by start-up companies such Dewpoint Therapeutics (cofounded by Hyman, biologist Richard Young of the Massachusetts Institute of Technology and Nobel laureate Phillip A. Sharp) and Nereid Therapeutics (which is building on Brangwynne's work), both based in Boston. "There is a ton of progress being made," Brangwynne says. "Condensate biophysics is now moving drugs into clinical trials."

Most of the attention so far has been on treatments for neurodegenerative diseases and cancer, but there are also efforts to combat viral infection via condensates. Some viruses seem to "hijack" condensate-forming proteins to help them replicate—so targeting those condensates could thwart the virus. In 2021 researchers in France and China showed that a drug that makes virus-induced condensates called inclusion bodies more solidlike can disrupt infection by RSV, the human respiratory syncytial virus.

IN 2023, when Brangwynne and Hyman were awarded the $3-million Breakthrough Prize for their work, it was surely a sign that condensates had arrived. "There's going to be a lot of cool stuff in the next 10 years," Alberti says. And although many questions about biomolecular condensates remain, these blobs are, in Drummond's view, "the revolution we have been waiting for."

It might seem odd that it took so long to see condensates for what they are. At least a part of the answer is that they don't fit into the picture of molecular biology that has prevailed for many decades. The old paradigm was all about how molecules pass information around the cell by getting together via selective interactions tightly encoded into their structure. Condensates undermine this view. They are loose, transient and flexible, and they show that many of the cell's key processes are conducted using molecular committees of many hundreds of members.

FROM OUR ARCHIVES
Designing Life.
Philip Ball; May 2023.
ScientificAmerican.com/archive

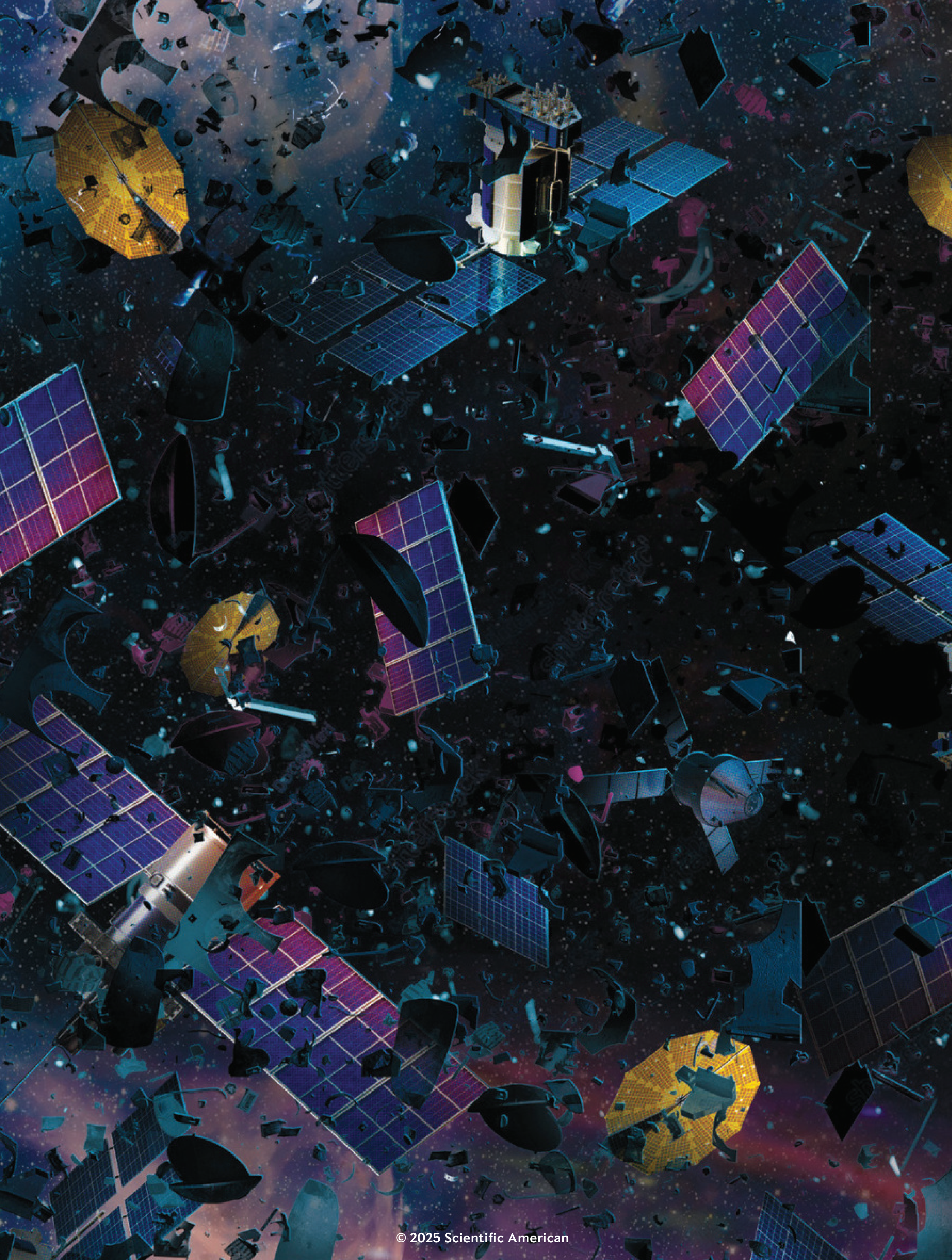
Schwille suspects that achieving molecular organization via condensates was probably critical in the origin of life itself, before nucleic acids and proteins had evolved to have precisely defined structures. For one thing, they show how cell-like compartments might have formed spontaneously from the progenitors of those polymeric biomolecules by liquid phase separation.

In fact, protein blobs like this were reported in 1929 by two Dutch chemists, who called them coacervates, and were invoked a few years later by Russian biochemist Alexander Oparin as the first primitive "proto-cells." Schwille says that such compartments, by sequestering some molecules away from others, could have set up the gradients in concentration that sustain living organisms in an out-of-equilibrium state.

Pappu speculates that catalytic condensates might have been important in such proto-living entities before proteins were themselves capable of acting as enzymes. Among the big questions for the future, Alberti says, is how evolution has subsequently made use of condensates. How do the forces of natural selection act on all the molecular players to alter and tune their ability to form condensates? "It's going to be fascinating to study," Alberti says. "You have to bring the evolutionary biology together with the physics."

Right now, though, condensates signal a new phase in our understanding of how life works at the molecular scale. "We now realize that [traditional] biochemistry and structural biology aren't going to be enough to describe what's happening in the cell, especially when we are dealing with processes that involve many components," Alberti says. We need to understand how all those components coordinate their interactions to create the unified entity that is the cell.

The blobs reveal an important scale on which that coordination happens: somewhere between the size of multicomponent complexes such as chromosomes and the size of whole cells. It's a scale where the molecules are no longer working like precise little machines but are instead gathering into a kind of material entity, governed by the collective physics of phase transitions yet still sensitive to the details of their molecular components. We don't yet know the rules dictating what goes on at these scales. But it's clearer than ever that life depends on them. ●



How to Recycle Space Junk

Orbital debris will become a crisis if we don't act soon BY MORIBA JAH

ILLUSTRATION BY TAYLOR CALLERY

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DECADE AGO humanity launched around 200 objects into space per year. Now we launch more than 2,600, with no prospects for slowing down. This rapid expansion of human activity in outer space has filled Earth orbit with space trash, from dead satellites to used-up rocket parts. The region is already so crowded that working satellites run the risk of colliding with bits of garbage from previous generations of spacecraft. Even the International Space Station often has to adjust its orbit to dodge debris.

Currently there are more than 25,000 pieces of trackable human-made junk larger than 10 centimeters orbiting Earth. The more we put up there, the greater the chance that pieces of debris (traveling at relative speeds up to 15 times faster than a bullet) will strike working spacecraft, creating even more dangerous trash. The catastrophic collision in 2009 between the defunct Russian satellite Cosmos 2251 and the operational Iridium satellite, for example, generated nearly 2,000 debris fragments, many of which are still being tracked today.

Orbital space is a finite resource, and it's rapidly being consumed by a few organizations, notably SpaceX, OneWeb and Amazon's Project Kuiper. SpaceX, for instance, owns and operates the majority of all working satellites, and the company aims to launch tens of thousands more satellites to provide global broadband Internet coverage. Similarly, Amazon plans to deploy 3,236 satellites for its broadband network.

If we keep up this pace, orbital space will become unusable—especially the most popular region, low Earth orbit (LEO), which extends up to 2,000 kilometers in altitude. When looking at all orbital regions, we may lose services we've come to rely on: continuous communications, GPS mapping, Internet, Earth monitoring, and more. Today nearly every satellite that is launched is equivalent to a piece of single-use plastic, in that its fate is to become detritus. We are heading toward a tragedy of the commons in orbital space: giving everyone unfettered access without global coordination and planning means that eventually no one may be able to use it.

As we continue to push the boundaries of space exploration and commercialization, there is a growing movement to rethink our approach to using the space environment—to move to a strategy anchored in stewardship and sound waste-management principles. I believe we must leave behind our "linear space economy," where we use and abandon, and move toward a "circular space economy"—a sustainable way to use space that emphasizes the reuse, recycling, and efficient management of space resources.

Moriba Jah is a celestial steward and space environmentalist. He is a professor of aerospace engineering at the University of Texas at Austin, as well as co-founder and chief scientist of space sustainability start-up Privateer and decision intelligence company GaiaVerse. His work focuses on the sustainable use of outer space, the development of innovative solutions to space debris, and providing decision intelligence to solve other environmental challenges.

JUST AS WE ARE RECKONING with how to conserve ecosystems on Earth for future living creatures, we must think of space as an environment worthy of preservation. In fact, reforming how we operate in space is critical for Earth conservation.

The production, launch and operation of satellites and rockets consume vast amounts of resources and energy, contributing to greenhouse gas emissions and environmental degradation. Rocket launches release pollutants into the atmosphere, including carbon dioxide, soot and aluminum oxides, which cause atmospheric damage and contribute to climate change.

Moreover, the practice of uncontrolled reentries, where defunct satellites and rocket stages are allowed to burn up in the atmosphere, adds to atmospheric

The ClearSpace-1 [illegible] Earth's atmosphere.

ClearSpace SA

pollution and creates the risk of debris falling on people and property on Earth. In 2024, for instance, pieces of a SpaceX Dragon service module, including one about the size of a standard car hood, landed in the mountains of North Carolina, and a castoff part of the International Space Station fell through the roof of a house in Naples, Fla.

A circular space economy would represent a paradigm shift toward sustainable space practices, drawing inspiration from circular economy ideas that are gaining traction here on Earth. “Circularity” in this sense refers to waste-management principles calling for the end of life of a product to be designed for the object’s reuse or recycling. The first step is to design spacecraft using materials that minimize pollution and generate less waste. The second is to repair satellites’ broken parts in orbit to extend their life cycles. The third is to recycle materials from defunct satellites for use on new missions, without having to bring the satellites back to Earth. And finally, we must retrieve and reprocess space debris to reduce collision risks and reclaim valuable components.

We won’t be able to enact a circular space economy without some technological innovations. We don’t currently have techniques to service all spacecraft in orbit, although several companies and space agencies are working on it. We must create technology to extend satellites’ operational lifespans and reduce the need for costly and resource-intensive replacement missions. We need spacecraft that can approach aging satellites and dock with them, using robots to repair, refuel and upgrade them.

We’ll also need a way to reuse and recycle satellites when their working lives are over. Currently all satellites become trash when their primary mission ends, and new satellites are built from entirely new materials. It’s a huge waste, much like our junkyards for used cars and other vehicles. Researchers are working on ways to harvest materials from dead spacecraft to integrate into new vehicles and to use techniques to build new satellites out of used parts.

A POSITIVE STEP in this direction is the reusable rocket technology SpaceX is developing. The boosters of their Falcon 9 rockets, for instance, can land vertically after being jettisoned in space after launch, allowing them to fly again. Not only does this save money—recycling boosters reduces the cost of each Falcon 9 launch by up to 30 percent—it generates less trash. But so far SpaceX is the only company or agency launching satellites with reusable rockets. We need more.

There’s also been movement toward servicing working satellites in orbit. Northrop Grumman’s SpaceLogistics has developed a spacecraft, the Mission Extension Vehicle (MEV), to help aging satellites keep going. In 2020 it successfully docked with the Intelsat 901 satellite, which was running out of fuel, and began using its own thrusters and propellant to maneuver the joined craft, extending the Intelsat’s operational life. A second MEV docked with another Intelsat spacecraft in 2021. When those satellites are ready to be retired, the MEVs can undock and move on to other spacecraft that need their help. Launching an MEV to aid an ailing craft costs about half to a quarter of the price of building and launching an entirely new satellite. In addition to saving money, in-orbit servicing reduces the frequency of new satellite launches, which in turn minimizes the accumulation of space debris and the greenhouse gas emissions that come with rocket launches.

Removing debris from orbit is another challenge. Different types of trash require different removal techniques, with many ideas coming from the fishing industry: some strategies use nets, others harpoons, and still others hooks. Each removal technology has limitations and works only for a subset of the objects that need to be fished out of orbital space. It's also really expensive to retrieve any kind of space trash because anything that is not being actively controlled in space is tumbling. This means that to grab something to remove it, you must either find a way to steady the space detritus or make your debris-removal satellite tumble along with it. Detumbling debris takes a lot of energy, which results in high propellant costs.

Nevertheless, some progress has been made. In 2021 a Tokyo-based company, Astroscale, ran the End-of-Life Services by Astroscale demonstration (ELSA-d) mission, which launched two satellites: one to simulate a dead spacecraft and a servicer satellite to remove it. The two craft successfully docked in orbit and then released, testing out a critical process for eventual debris removal. The company plans to run more tests with its Active Debris Removal by Astroscale-Japan (ADRAS-J) mission, which launched in 2024.

The European Space Agency (ESA), partnering with start-up ClearSpace, is set to launch its ClearSpace-1 mission in 2028. ClearSpace-1 will use four robotic arms to grab onto the agency's PROBA-1 satellite and bring it safely out of orbit. The project aims not only to clean up space but also to develop the ability to target larger and more complex pieces of debris.

Finally, more efficient propulsion technology allows spacecraft to use less fuel and last longer on their initial load. Electric propulsion systems, such as ion thrusters and Hall effect thrusters, are newer technologies that offer higher efficiency and fuel economy compared with traditional chemical propulsion. These systems use electric power to ionize propellant and generate thrust, enabling spacecraft to achieve higher velocities and perform precise maneuvers over extended periods. Electric propulsion is already used by many working satellites and will become increasingly common.

As we design new technology to conserve space, we'd do well to take inspiration from another kind of tech: Indigenous societies' traditional ecological knowledge (TEK). This kind of TEK emphasizes the importance of harmonious relationships between human activities and the environment. It shows us that we have to see space as an extension of our natural world, where resources must be managed wisely and responsibly.

An example of applying TEK ideas to modern space activities is a recent collaboration between the ESA and Indigenous groups in Australia to study the impacts of space debris on wildlife habitats. By respecting the wisdom of Indigenous communities, ESA not only advanced their scientific goals but also promoted a sustainable model that can be applied to future space missions.

NEW TECHNOLOGY ALONE isn't enough to fix the space junk problem—we'll need legal reform, too. The current global space policy is a patchwork of regulations that often lag behind technological advancements and the evolving needs of space activities. SpaceX, for instance, has faced regulatory challenges in deploying its reusable rockets because our laws haven't caught up with the technology. Fragmented regulations across different countries and regions also lead to inconsistencies and hinder international collaboration. And many existing space policies don't even address sustainable practices such as in-orbit servicing, space debris mitigation and responsible resource use.

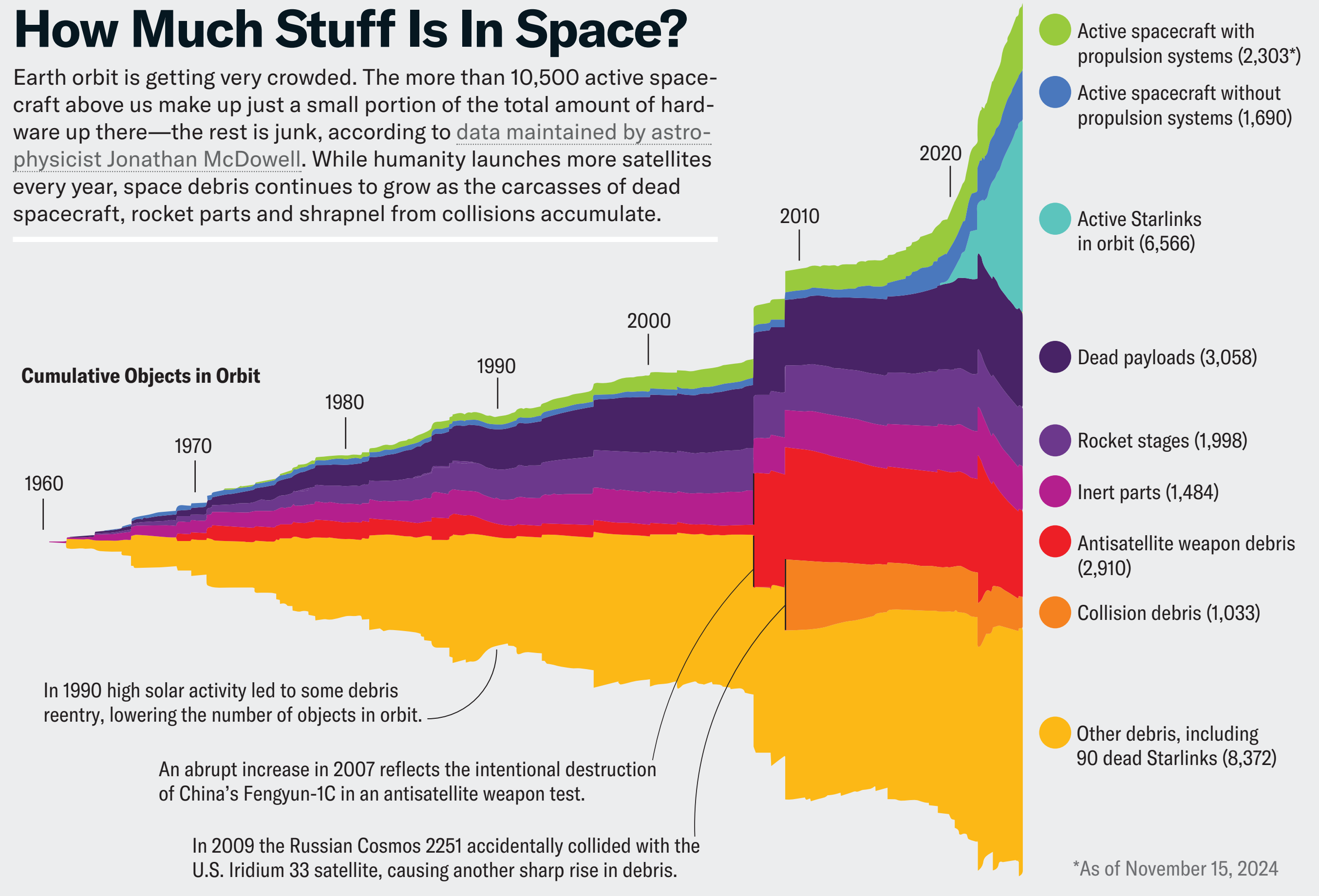
The European Union is trying to pave the way by integrating sustainability principles into its space policies. The E.U. has streamlined licensing processes for satellite launches and in-orbit operations across member states and has allocated significant funding for research and development on dealing with space debris. The U.S., through its many government agencies, has begun working to streamline the licensing process as well. But most countries are dangerously far behind.

Governments have a strong hand to play in incentivizing companies to design and develop sustainable space systems. One way to do this would be to adopt what are called extended producer responsibility laws, which require companies to help manage the waste from the technology they produce. Perhaps governments could use a credit system to regulate the amount of space debris the industry is allowed to create. Laws could also incentivize the design, launch and operation of on-orbit recycling centers where aging and defunct satellites could be repurposed.

Ultimately the governments that permit spacecraft to be launched are liable for any damage their space objects may cause. So the responsibility for cleaning orbital space falls to governments, but none of them, including Russia, the U.S. or China, are establishing robust markets for space garbage pickup and removal services. Moreover, currently there is no legal mechanism to transfer this liability for damage from one launching state to another, making it complicated to put in place a space salvage law analogous to maritime policy. The United Nations Committee on the Peaceful Uses of Outer Space also plays a pivotal role in developing international space law and norms. Its Space Debris Mitigation Guidelines encourage member states to manage space debris and promote sustainable space operations. More than 100 countries have endorsed the guidelines, including the U.S. Yet guide-

How Much Stuff Is In Space?

Earth orbit is getting very crowded. The more than 10,500 active spacecraft above us make up just a small portion of the total amount of hardware up there—the rest is junk, according to data maintained by astrophysicist Jonathan McDowell. While humanity launches more satellites every year, space debris continues to grow as the carcasses of dead spacecraft, rocket parts and shrapnel from collisions accumulate.



lines are not enforceable laws in and of themselves—they are merely suggestions.

Space exploration also raises fundamental ethical questions about fair resource extraction, ownership and environmental stewardship. Asteroid mining, for example, presents opportunities for accessing rare minerals and resources, although it also risks destroying the scientific and cultural heritage of celestial bodies. And space mining could destabilize global markets—imagine mining an asteroid made out of platinum. Furthermore, who should be allowed to profit from the resources of asteroids—is it fair for only certain countries, or certain billionaires, to grow even richer and more powerful from space commodities?

Organizations such as the International Institute of Space Law and the U.N. Office for Outer Space Affairs are trying to develop ethical guidelines for responsible ways to use space resources that emphasize transparency, international cooperation and sustainability. Initiatives such as the Space Sustainability Rating, which aims to certify space missions based on sustainable practices, could encourage companies and nations to act responsibly.

PRESERVING THE SPACE ENVIRONMENT for future generations is a moral imperative. In the short term, we must take immediate action to deal with the growing dangers of space junk. We need more funding for debris-tracking and debris-mitigation technologies. We must also start changing how we build and use satellites to waste fewer resources, produce less trash and pollution, and recycle more. A circular space economy is the only way to keep space usable indefinitely.

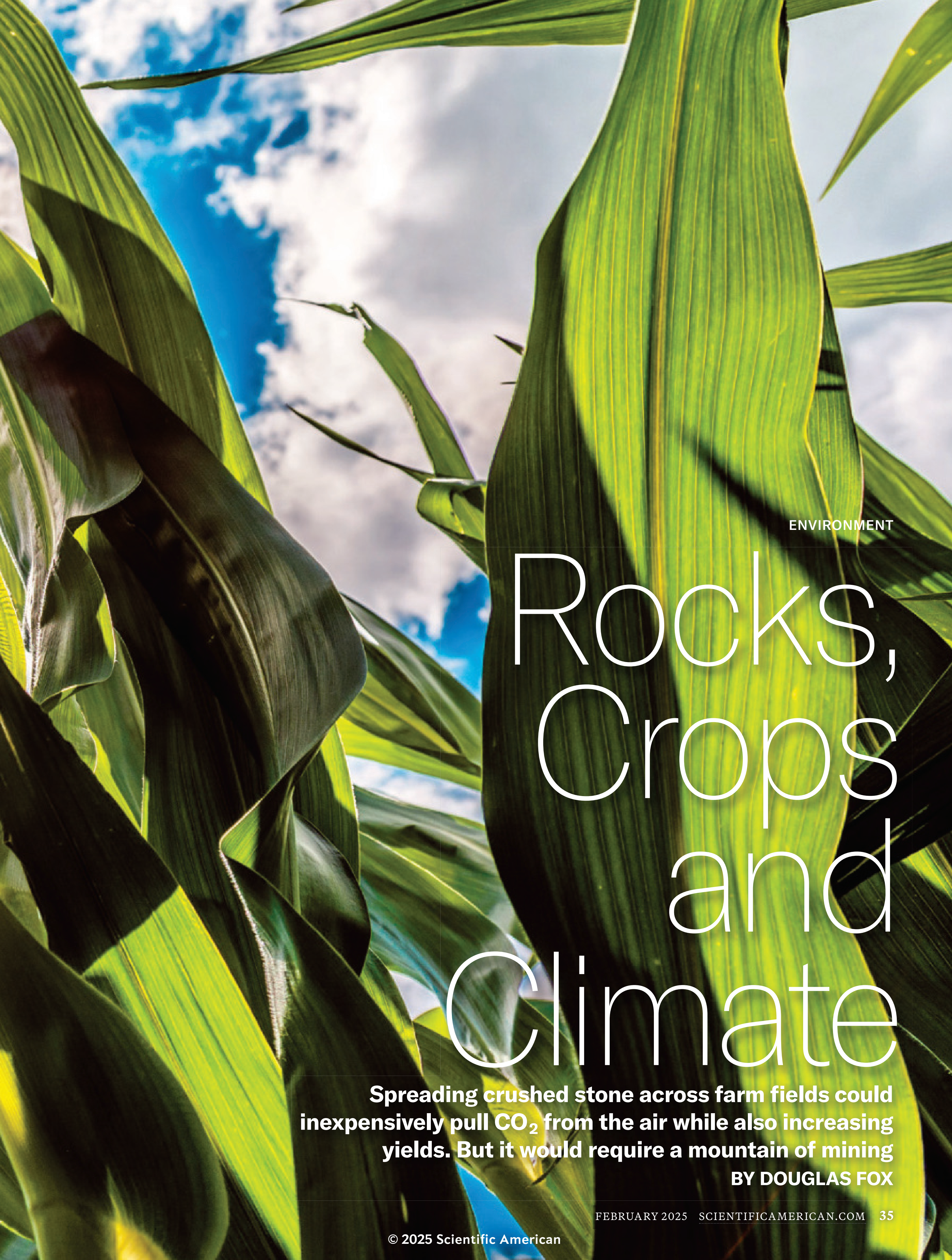
In the long term, fostering international cooperation—and international treaties requiring sustainable space practices—is critical. The Inter-Agency Space Debris Coordination Committee, an intergovernmental organization dedicated to combating the problem of orbital trash, is a promising step. Many space agencies, including NASA, China's National Space Administration and Roscosmos, are members. The ESA's Clean Space initiative is another smart approach to reducing space debris through technology development and policy changes.

The establishment of a circular space economy is not just an option but a necessity for the sustainable future of space exploration. By adopting the principles of reuse, recycling, and efficient resource management, we can lower the risks of space debris collisions, preserve resources, and ensure that outer space remains a viable domain for scientific discovery and commercial innovation. Policymakers, industry leaders, scientists and the global community must embrace a sustainable approach to our activities in Earth orbit, securing its potential for generations to come. ●

FROM OUR ARCHIVES
Space Junk Piles Up. Mark Fischetti; February 2019. ScientificAmerican.com/archive

Source: "Satellite Statistics: Satellite and Debris Population," Jonathan's Space Report (*data*)

Graphic by Jen Christiansen



ENVIRONMENT

Rocks, Crops and Climate

Spreading crushed stone across farm fields could inexpensively pull CO_2 from the air while also increasing yields. But it would require a mountain of mining

BY DOUGLAS FOX

T**HE SCENE THAT UNFOLDED ON A COLD NOVEMBER DAY IN CENTRAL ILLINOIS** might seem commonplace, but it was part of a bold plan to pull billions of tons of carbon dioxide from the atmosphere and stuff it into the ocean.

A few miles south of Urbana a dump truck trundled past bare fields of dirt before turning into an adjacent lot. It deposited a cottage-size mound of grayish-blue sand—190 metric tons of a crushed volcanic rock called basalt. Farmers spread the pulverized basalt across several fields that they sowed with corn months later. This was the fourth year of an ambitious study to test whether the world's farmlands can be harnessed to simultaneously address three global crises: the ever rising concentration of planet-warming CO_2 in the atmosphere, the acidification of the oceans and the shortfall in humanity's food supply.

The trial results, published in February 2024, were stunning. David Beerling, a biogeochemist at the University of Sheffield in England, and Evan DeLucia, a plant physiologist at the University of Illinois Urbana-Champaign, led the study. They found that over four years, fields treated with crushed basalt and planted with alternating crops of corn and soy pulled 10 metric tons more CO_2 per hectare out of the air than untreated plots. And crop yields were 12 to 16 percent higher. In other research, they found that adding crushed basalts to soils improved the harvest of miscanthus, a tall grass that is used to make biofuels, by 29 to 42 percent, and the fields captured an estimated 8.6 metric tons of CO_2 per hectare of land each year, compared with untreated fields. "It was exciting," Beerling says. "We were pleasantly surprised."

Their findings added to positive results elsewhere. In 2020 researchers in Canada reported that adding the mineral wollastonite to fields growing lettuce, kale, potatoes and soy sequestered CO_2 in the soil at rates as high as two metric tons per hectare per year. And last spring Kirstine Skov, a natural geographer at the start-up company UNDO Carbon in London, showed that crushed basalts improved the yields of spring oats by 9 to 20 percent while reducing soil acidity in several fields in England.

Scientists, start-up companies and large corporations are experimenting with elaborate technologies to slow global warming: High-altitude planes that release sulfur dioxide into the stratosphere to block some incoming sunlight. Machines on Earth's surface that pull CO_2 out of the atmosphere. Iron sprinkled across the sea that enhances the growth of algae that absorb CO_2. These deployments could buy humanity some extra time to transition from fossil fuels to clean energy while preventing the climate from crossing dangerous thresholds in a permanent way. But the exotic approaches require gobs of money and energy or could threaten ecosystems. Simply spreading crushed rock on fields—as farmers have done for centuries with lime—seems refreshingly low tech. "That's part of its elegance," Beerling says.

The basalt in Illinois came from a quarry in southern Pennsylvania, where it is mined for roofing and building materials. Basalt is the most abundant rock in Earth's crust. As it naturally weathers—gradually dissolving in soil water—it captures CO_2, converting it into bicarbonate ions in the water, which cannot easily reenter the atmosphere. The reaction also releases into the soil nutrients that are important for plant health, including calcium, magnesium and silicon. Grinding and spreading basalt—an approach known as enhanced rock weathering (ERW)—speeds up those processes greatly. It could help cash-strapped farmers around the world by increasing crop yields, reducing fertilizer use and potentially allowing them to sell carbon credits.

If ERW were to be scaled up globally, it could remove up to two billion metric tons of CO_2 from the air every year, according to Beerling. That would cover a significant share of the atmospheric carbon humanity must draw down to keep temperature rise

Douglas Fox
writes about biology, geology and climate science from California. He wrote the November 2022 article "The Coming Collapse," which revealed that Antarctica's Thwaites Ice Shelf could splinter apart in less than a decade.

Jared Unverzagt/Getty Images (*preceding pages*)

A worker spreads pulverized basalt on a recently harvested cornfield in central Illinois.

Jordan Goebig/University of Illinois

to 1.5 degrees C, widely acknowledged as the necessary goal to prevent widespread catastrophe. But ERW would require mining and crushing billions of tons of rock every year—enough to build a mountain—and transporting it to farms, all of which would release CO_2. Still, calculations suggest that those emissions would pale in comparison to the amount of CO_2 that the rock stores away for centuries or longer—sequestered more permanently than it could have been in a forest of trees.

ERW is newer than the other so-called negative emissions strategies, and so far only a few trials have been fielded. Yet companies are already looking to sell carbon credits tied to the technique. Noah Planavsky, a biogeochemist studying enhanced weathering at Yale University, sees promise in these unsettled circumstances. But he worries that if ERW expands too quickly, before the technique is refined, it could produce disappointing results and generate a backlash. "This has the potential to be something truly impactful," he says. "And there are so many ways you can imagine it going poorly."

THE IDEA OF ERW is based on a fundamental insight about how Earth naturally functions. Across geological time, lava eruptions spewed huge amounts of CO_2 into the atmosphere, heating the planet. Subsequent weathering of the erupted rock over millions of years pulled the gas out of the atmosphere, cooling the planet back down. Basalts are effective in capturing CO_2 because they are high in calcium and magnesium from deep in the planet. Today vast swaths of North and South America, Africa, Asia, and other areas are covered in these solidified lavas.

Scientists have long wondered whether humans could accelerate CO_2 removal by speeding up rock weathering. In 1995 Klaus Lackner, a physicist then at Los Alamos National Laboratory in New Mexico, proposed heating basalts to absorb CO_2 more quickly. Over time this basic idea fermented into other forms: injecting concentrated CO_2 into hot layers of basalt underground where they would form carbonate minerals, or spreading powdered basalt across the ocean, which would absorb CO_2, sinking the carbon.

In the late 2000s Phil Renforth, a Ph.D. candidate at Newcastle University in England, noticed that the demolished remnants of steel mills in his area accumulated white crusts of carbonate minerals on the ground. Fragments of steel slag and concrete, both high in calcium, were reacting with CO_2. In 2013 he and Jens Hartmann, a geochemist then at the University of Hamburg in Germany, published a paper suggesting that calcium-rich rocks could be crushed and spread on farmland to capture CO_2 while also improving soils.

At about that time, Beerling was studying how grasslands influence the weathering of bedrock and the natural capture of CO_2. When he read Renforth and Hartmann's paper, he realized he could use his model to predict how basalt weathering would unfold on farmlands. In 2016 Beerling published calcu-

Seeing how this landed with the public and press "strengthened our belief that this was the right way to go."
—DAVID BEERLING *UNIVERSITY OF SHEFFIELD*

lations predicting that a millimeter or two of basalt dust spread annually over the world's tropical lands could reduce CO_2 levels by 30 to 300 parts per million (ppm) by 2100. Atmospheric carbon dioxide is currently around 425 ppm—up from 280 ppm before the industrial revolution—and is expected to hit 500 to 1,200 ppm by 2100. The modeling suggested that ERW could prevent 0.2 to 2.2 degrees C of warming by that date.

Common climate scenarios predict that if humans are going to limit warming to two degrees C, we need to remove five to 10 gigatons of CO_2 from the atmosphere annually by 2050. In 2018 Beerling's team published updated calculations predicting that if crushed basalt were spread yearly across 700,000 square kilometers of corn and soy croplands in the U.S., it could remove 0.2 to 1.1 gigatons of CO_2 from the atmosphere annually.

In 2020 Beerling and his collaborators, joined by Renforth, published a refined analysis in *Nature*. They estimated that if two gigatons of CO_2 a year had to be captured worldwide through ERW, China, India, the U.S. and Brazil could cover 80 percent of that amount, even after accounting for the CO_2 emitted while mining, crushing and transporting the rock. Obviously a combination of carbon capture methods would be needed to reach 10 gigatons a year. But, Beerling says, "If you can do two [gigatons] of it with enhanced weathering and improve food security and soil health, that's 20 percent of the way there."

The Illinois trial provided strong validation. Farming of corn and soy typically releases CO_2 through the respiration of roots and soil microbes, but the basalt-treated corn-soy fields released 23 to 42 percent less CO_2. Multiplied across the U.S., that's 260 million tons of CO_2 potentially avoided each year.

Unlike geoengineering approaches such as hoisting sulfur into the sky or scattering iron across the sea, which people often view as risky tinkering with nature, ERW was well received when papers were published, Beerling says. "It was important to see how this landed with the public and the press," he says. The reactions "strengthened our belief that this was the right way to go."

ERW is fundamentally different from two other soil-based carbon strategies that have been around longer. In a method called biochar, farmers partially burn leftover plant matter, turning it to charcoal—nearly pure carbon—which is plowed into the dirt for long-term storage. In the second method, leftover plant material is plowed back into the soil without being charcoaled; this stores carbon as organic molecules that can nourish crops, although the molecules can also return to the atmosphere.

ERW traps CO_2 as dissolved bicarbonate in soil water, which eventually runs off farm fields into streams that ultimately lead to the sea, storing CO_2 in the ocean water as bicarbonate or as solid carbonate minerals on the seafloor. Studies predict that ERW would reliably store bicarbonate in the ocean for 100 to 1,000 years, which could also help reduce climate-related ocean acidification. What's more, ERW could alleviate another major problem, not addressed by the two other methods, that plagues farmers around the world.

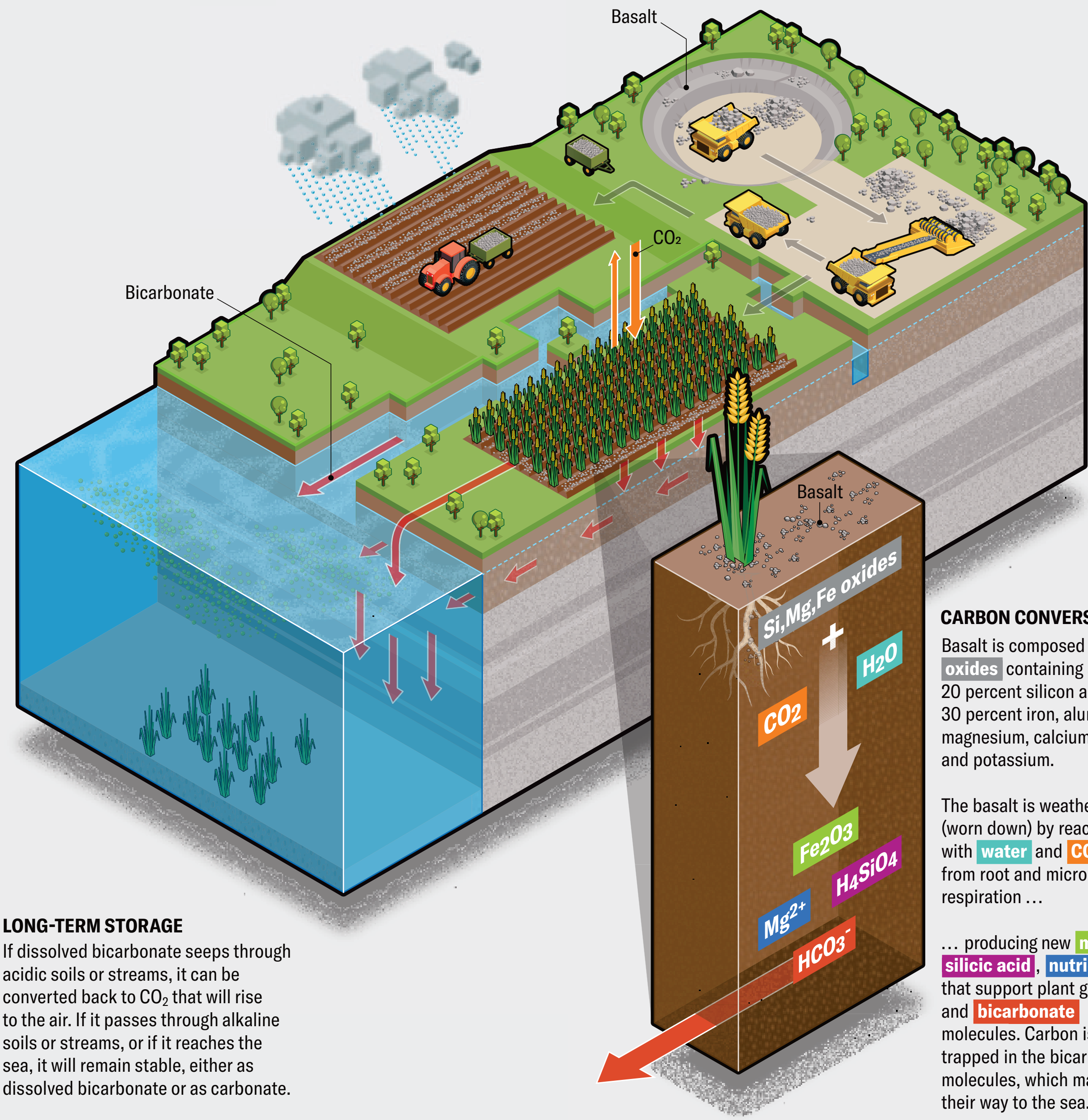
ONE OF THE MOST STRIKING EXAMPLES of how rock weathering has regulated atmospheric CO_2 levels over the eons can be found along the western coast of India—one reason some of the earliest efforts to roll out ERW by start-up companies are happening in this country. India's coastal plain, dotted with rice paddies and villages, abruptly rises 1,000 meters through a chaotic maze of sharp ridges, V-shaped canyons, rushing rivers and waterfalls to a high plateau. The canyon walls are striped in alternating layers of yellow and brown basalt, marking the edge of the Deccan basalts, formed from a massive series of lava flows that started around 66 million years ago. By 50 million years ago Earth was unusually warm, with CO_2 levels nearly four times what they are today. Around that time, the Deccan basalts began altering the planet's climate in a slow but potent way. Continental drift carried them into the equatorial belt, where abundant rainfall and warm temperatures caused the rocks to weather more quickly. The weathering minerals pulled CO_2 from the air and washed it down rivers to the sea, trapping it there.

Over the next 30 million years, estimates indicate, weathering basalts drew more than one million gigatons of CO_2 from the atmosphere, some of it becoming buried as carbonate on the seafloor. Atmospheric CO_2 declined, temperatures cooled, and an ice sheet began growing across Antarctica.

The village of Sarekha Khurd, in central India's Madhya Pradesh state, sits near the eastern, inland edge of the Deccan basalts. The people there have farmed rice for centuries, in a patchwork of paddies divided by rows of teak and red-blossomed gum trees. Many of the farmers live tenuously, working little plots the size of one to two soccer fields. They earn an average of $1,500 a year, spending up to 30 percent of that on fertilizers and other chemicals. And they face constant hazards. Heat waves as high as 48 degrees C (118 degrees Fahrenheit) can stunt crops and disrupt needed monsoon rains. Constant agriculture has slowly acidified the dark, rich soils, depleting their stores of calcium and magnesium, as

How Enhanced Rock Weathering Works

Crushed basalt rock spread across farm fields could help draw carbon dioxide from the atmosphere, easing global warming. It could also enhance soil nutrients, which could raise crop yields. Carbon is stored long term as it reacts with water in the soil and eventually runs off into the sea, although it is difficult to predict how much capture would occur.



CARBON CONVERSION
Basalt is composed of **oxides** containing around 20 percent silicon and 30 percent iron, aluminum, magnesium, calcium, sodium and potassium.

The basalt is weathered (worn down) by reaction with **water** and **CO_2** from root and microbial respiration …

… producing new **minerals**, **silicic acid**, **nutrients** that support plant growth, and **bicarbonate** molecules. Carbon is trapped in the bicarbonate molecules, which make their way to the sea.

LONG-TERM STORAGE
If dissolved bicarbonate seeps through acidic soils or streams, it can be converted back to CO_2 that will rise to the air. If it passes through alkaline soils or streams, or if it reaches the sea, it will remain stable, either as dissolved bicarbonate or as carbonate.

farmers harvested plants rather than leaving them to decay and return their minerals to the soil. The average pH of soils in this area is slightly acidic, around 6.4 (7.0 is neutral), similar to saliva. This is not ideal for growing rice because acidification impairs the plants' absorption of nutrients, such as phosphorus, and it may even alter the mix of soil microbes, allowing pathogenic bacteria or fungi to spawn disease outbreaks that can damage crops.

Farmers worldwide have dealt with soil acidity since long before they understood it. Dozens of pits found in the forests north of Paris suggest that as early as 6,000 years ago, farmers dug into the limestone bedrock and scattered pieces of it on the fields where they grew wheat, barley and peas. Later on, Romans would scatter chalky calcium carbonate rocks onto croplands to reverse "sour" soil. For centuries farmers in Europe and North America neutralized acidity by sprinkling fields with crushed limestone, rich in carbonate.

Paul Nelson/James Cook University (*scientific reviewer*)

Graphic by Ben Gilliland

> “Imagine the farm of the future. Part of the farmer’s view of their mandate is carbon dioxide removal.”
> —NOAH PLANAVSKY *YALE UNIVERSITY*

But people in many areas, including India, don’t have easy access to limestone. And the process of neutralizing acidic soil with lime can potentially release CO_2 into the air. In such places, ERW is appealing because it can reverse that dynamic, converting airborne CO_2 into dissolved bicarbonate in soil.

Last May farmers in Sarekha Khurd started trying ERW. Workers with Mati Carbon, an ERW start-up based in Houston, Tex., trucked in 1,250 metric tons of crushed rock from nearby quarries that mine the Deccan basalts for road construction materials. The company is currently providing basalt, free of charge, to more than 180 farm villages in Madhya Pradesh and its neighboring state of Chhattisgarh. They plan to add more basalt each year. Rice yields have increased by 15 to 20 percent on average, and in some cases by up to 70 percent.

Mati Carbon recently expanded its operations to a handful of villages in Tanzania and Zambia. “Our mission is the farmer,” says Mati founder Shantanu Agarwal, especially “these smaller, climate-vulnerable farmers.” The company hopes to earn money by selling carbon credits. Agarwal and Jacob Jordan, Mati’s lead scientist, estimate that improved soils, increased crop yields and reduced spending on fertilizers could raise poor farmers’ income by 10 to 30 percent, making them less vulnerable.

As promising as early trials have been, a large-scale rollout of ERW would have to overcome some stark realities, starting with the staggering amount of rock it would require. Beerling’s calculations suggest that if ERW were used to capture two gigatons of CO_2 a year, it would consume 13 gigatons of basalt annually—about 4.5 cubic kilometers of rock, roughly equal to the volume of the Matterhorn. That would require 30 percent more mining than the 40 gigatons or so of sand, gravel and crushed rock that are now quarried worldwide annually for industry. Such an increase might not be possible for some kinds of rock, but the world’s reserves of basalt are truly vast, distributed widely across the planet.

Crushed basalt that’s already produced in quarries as an unused by-product could pick up some of that slack. So could calcium-rich industrial by-products, such as crushed concrete, mine tailings, ash from sugarcane milling and coal burning, and wastes from cement, aluminum and steel production. But many of these by-products contain chromium, nickel, cadmium, and other toxic elements, so they could maybe be used to capture CO_2 in factory yards or tailings piles at mines but not on croplands. When additional basalt mining and crushing is needed, it will cost about $10 and emit around 30 kilograms of CO_2 per ton. Beerling’s team considered these factors when it estimated that ERW would cost $80 to $180 per ton of CO_2 captured, after emissions are subtracted.

But there will be other costs. In China and India—two countries with the most agricultural potential for ERW—the thriving rock-quarrying industries have been criticized for poor protection of human rights. India’s sandstone-quarrying industry, for example, employs more than three million people. A 2020 report published by the Washington, D.C.–based Center for Human Rights found that many of them are bonded laborers—people who work at low wages to repay loans with annual interest rates up to 20 percent, making it difficult to ever repay debts and trapping them in the job. Such workers may face dangerous temperatures, rock collapses and swirling mineral dust.

A 2022 study found that quarry workers in northeastern India suffer poor lung and heart health, with low levels of blood oxygen, high pulses and poor lung airflow. If a quarry worker is injured, dies or falls ill, wives or children may be forced into work to repay the debt. These problems aren’t limited to India, says Bhoomika Choudhury, a lawyer and labor researcher with the Business & Human Rights Resource Center in Dubai, who wrote the 2020 sandstone report: “We are seeing these patterns everywhere” in countries across Asia, Africa and South America.

Any large increase in quarrying would also translate into more landscapes being torn up—some of them in potentially sensitive areas—although this is also true for other materials that will have to be mined to support the broader transition to renewable energy, such as lithium, cobalt, graphite and rare earth elements. It is also possible that even if mining challenges are surmounted, ERW won’t work as well worldwide as it has in the small trials that have been done thus far. For example, many scientists assumed ERW would work best in the warm, wet tropics, where basalt weathers more quickly. But two recent studies complicate that picture.

A 2022 trial that Beerling’s group supported in Malaysia, where basalt dust was spread across parts of a palm oil plantation, produced inconclusive results. Beerling suspects that the benefits are being temporarily masked by local conditions. The dark, pungent soils contain more decaying organic matter and more clay than the soils in Illinois; those charged materials can latch on to the breakdown products of basalt, keeping them from converting CO_2 into bicarbonate. “There’s a delay in capturing carbon dioxide,” Beerling says. It doesn’t happen until the soil’s capacity to bind the dissolving minerals has been saturated, “which may take a year or take five years,” he says. This remains to be seen.

Deepak Kushwaha/Mati Carbon

Two farmers harvest rice from paddies in India that had been treated with ground-up rock. Rice yield was about 25 percent higher than in the past, when no rock was spread.

Acidity is the other complicating factor, according to a trial on tropical sugarcane fields in northeastern Australia. The soil there is acidic, so it can potentially consume the basalt before it has a chance to react with CO_2. Initial results, published last October, show that CO_2 capture rates are only about 1 percent of those in Illinois. Paul Nelson, a soil scientist at James Cook University in Cairns who helped lead the study, says it may be hard to fix the problem just by neutralizing acidic soils before adding basalt because in wet tropical areas the acidity may extend many meters down, to the bedrock.

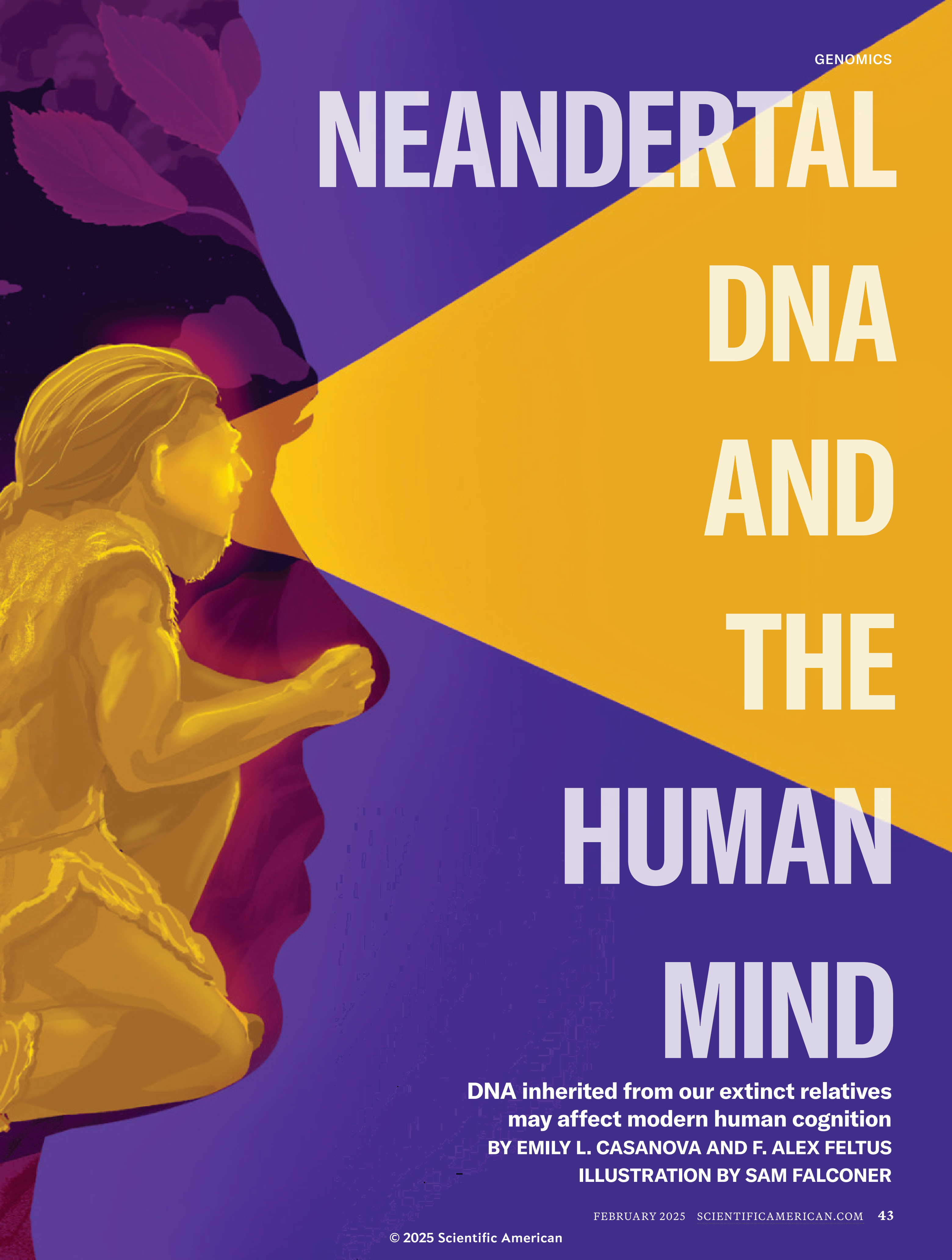
Right now researchers are just trusting that wherever ERW is done, from Illinois to Australia, the CO_2 that is captured as dissolved bicarbonate will seep into streams, flow through rivers and reach the ocean without encountering a highly acidic environment. If it does flow through an acidic environment, Nelson says, some of it "could be converted into CO_2 along the way," returning to the atmosphere.

DESPITE THE UNCERTAINTIES, some two dozen companies have emerged to try to exploit ERW. Many are selling anticipated carbon-capture credits, in some cases to companies such as Microsoft and Stripe that hope to zero out their carbon footprint. This activity makes Planavsky, the Yale biogeochemist, uneasy. He's aware of lessons learned in another carbon market that grew too quickly. In recent years companies have sold more and more "voluntary carbon offsets" for protecting forests, but some of the projects have subsequently been revealed as worthless. ERW is "a potentially really valuable opportunity" to remove CO_2, Planavsky says, "but it's not going to work everywhere." If companies cut corners, he says, ERW could "blow up on the launch pad."

Yet for ERW to have a large impact by 2050, it will need to expand quickly, says Gregory Nemet, an energy scientist at the University of Wisconsin–Madison. Last May he and his colleagues published a study analyzing the combined potential of novel CO_2 removal methods such as ERW, direct air-capture machines and the use of biofuels with CO_2 captured from smokestacks. Between now and 2050 these methods need to grow "by something like 40 percent per year, every year," Nemet says. That sounds extreme, although he says that electric cars and solar energy have expanded even more rapidly for 10 or 20 years. And if enhanced weathering ends up costing \$80 to \$180 per ton of CO_2, as Beerling's group predicted, it may be cheaper than direct air capture (\$400 to \$1,000 per ton right now), and similar to biofuels with smokestack capture (\$100 to \$300 per ton today).

If ERW does pan out on a large scale, Planavsky—whose family farms—sees potential societal benefits that go beyond CO_2 removal. Building machines that capture CO_2 from the air or from smokestacks will generate profits for big companies. But with a low-tech approach like ERW, even small farmers could sell carbon credits. "Imagine the farm of the future," he says. "Part of the farmer's view of their mandate is carbon dioxide removal." ⬣

FROM OUR ARCHIVES
The Carbon Rocks of Oman. Douglas Fox; July 2021. Scientific American.com/archive



GENOMICS

NEANDERTAL DNA AND THE HUMAN MIND

DNA inherited from our extinct relatives may affect modern human cognition

BY EMILY L. CASANOVA AND F. ALEX FELTUS

ILLUSTRATION BY SAM FALCONER

W **HEN NEANDERTALS WERE FIRST DISCOVERED** nearly 170 years ago, the conceptual gap between their lineage and that of modern humans seemed vast. Initially scientists prejudicially believed that the Neandertals were primitive brutes hardly more intelligent than apes and that their lack of advanced thinking had doomed them to extinction. Since that time, researchers have amassed evidence that they shared many of the cognitive abilities once considered unique to our species, *Homo sapiens.* They made complex tools, produced staples such as flour, treated their ailments with plant-based medicines, used symbols to communicate and engaged in ritual treatment of their dead.

The divide between their lineage and ours narrowed even further in 2010, when researchers published the first Neandertal genome sequence. Comparison of that ancient DNA with modern human DNA showed that the two species had interbred and that people today still carry the genetic fingerprint of that intermixing. Since then, numerous studies have explored the ways in which Neandertal DNA affects our modern physiology, revolutionizing our understanding not only of our extinct cousins but of ourselves as a hybrid species.

This area of research, clinical paleogenomics, is still in its infancy, and there are many complexities to unravel as we explore this new frontier. We therefore must take the findings from these studies with a grain of salt. Nevertheless, the research conducted to date raises the fascinating possibility that Neandertal DNA has wide-reaching effects on our species—not only on general health but on brain development, including our propensity for conditions such as autism. In other words, DNA from our extinct relatives may, to some extent, shape the cognition of people today.

Emily L. Casanova is an assistant professor of neuroscience in psychology at Loyola University, New Orleans. She studies autism from various perspectives.

F. Alex Feltus is a professor of genetics and biochemistry at Clemson University. He studies the genomic mechanisms underlying observable traits.

IT SEEMS THAT every few weeks a new study expands our understanding of how Neandertal DNA affects modern human health and physiology. Researchers have found that some Neandertal DNA makes carriers more vulnerable to various immune disorders, such as systemic lupus erythematosus and Crohn's disease, and some gene variants affect an immune molecule known as interleukin-18, which plays a role in predisposition to autoimmune disorders. Some Neandertal DNA variants are implicated in increased risk for severe COVID, whereas others appear to be protective factors. Still other Neandertal-derived variants may be instrumental in determining whether we develop allergies. And there is some evidence to suggest that our ancient cousins' DNA may even be implicated in asthma—a subject of ongoing research.

Scientists have also documented a number of effects of Neandertal DNA beyond the immune system. Neandertal DNA may affect the color of our skin and hair, how readily our blood clots, our propensity for heart disease, and how our cells respond to various environmental stressors such as radiation. It can also help determine how prone we are to certain skin cancers, thiamine (vitamin B_1) deficiency, obesity and diabetes.

The notion that Neandertal DNA might significantly influence our brains and behavior, however, is actually a bit counterintuitive. Previous research has shown that this ancient DNA tends to be underrepresented in the brain-related genes of modern humans, primarily because these types of genes are very sensitive to change, and anything new gets weeded out fairly quickly. These regions of the genome are known as Neandertal DNA deserts. Yet studies published over the past decade have shown that some Neandertal DNA has in fact persisted in and around some brain-related genes in modern humans.

The effects of this DNA are apparent throughout the brain and associated structures. Philipp Gunz of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, and his colleagues found that people with higher percentages of Neandertal DNA are more likely to have skull shapes that are modestly elongated and reminiscent of the Neandertal skull, particularly around the parietal and occipital regions toward the back of the cranium. This skull elongation is sometimes associated with Neandertal variants that are located near the genes *UBR4* and *PHLPP1,* which are involved in neuron production and the formation of myelin, the fatty sheath that insulates the axons of larger neurons, allowing them to communicate more reliably over longer distances. The skull elongation is also associated with Neandertal variants located near *GPR26.* This gene is still poorly understood, but it appears to have antitumor effects and is therefore probably also involved in regulating the production of neurons and other nervous systems cells called glia.

In another study, Michael D. Gregory of the National Institutes of Health and his colleagues observed differences in the structure of the brain in regions related to visual processing and socialization. Specifically, people with more Neandertal DNA tend to have increased connectivity in visual-processing tracts but reduced connectivity in nearby tracts that are implicated in social cognition. This intriguing finding suggests there could be trade-offs between visual processing and social skills in the *Homo* lineage.

Of particular importance, Neandertal DNA also seems to influence the structure and function of the cerebellum. Although most neuroscientists have tended to think of this brain region as functionally dedicated to motor memory and coordination, it is also involved in attention, emotional regulation, sensory processing and social cognition. The cerebellum seems to be vital for systems involved in mentalizing, which underlies many aspects of our ability to infer the mental states of other people. In 2018 Takanori Kochiyama of Advanced Telecommunications Research Institute International in Kyoto and his colleagues published a study in which they reconstructed the crania of Neandertals and those of early modern humans and compared them. Their research showed that the cerebellum was significantly smaller in our extinct cousins than in members of our own lineage. These data suggest that there could be significant variability in the structure and function of the cerebellum (and therefore in social cognition) in modern humans as a result of the DNA we have inherited from Neandertals.

The effects of Neandertal DNA are apparent throughout the brain and associated structures in people today.

WHEN IT COMES TO the inheritance of genetic variations, the overall size of a population has a dramatic effect on whether a particular DNA mutation is passed on, especially if it's somewhat deleterious or harmful. In a large population, a modestly deleterious mutation is likely to get weeded out relatively quickly just by sheer probability. But in a small, isolated population, such a mutation is far more likely to spread as if it were neutral, and it may even become permanently retained in the population. Small groups tend to accumulate more mutations over time than larger populations do, which may reduce the number of children that individuals in those populations can raise, putting the groups at risk of dying out. It's for this reason that most modern human cultures consider it taboo to marry a close relation such as a first cousin. Cultures that still allow this practice often have unusually high rates of so-called recessive diseases, which arise when an individual inherits the same genetic susceptibility factor from both parents.

Research into the Neandertal genome has indicated that our extinct relatives underwent a significant and somewhat protracted reduction in their population size, an event known as a genetic bottleneck. Between 50,000 and 40,000 years ago, their population dwindled to perhaps as few as 5,000 individuals. Because of that genetic bottleneck, the Neandertal genome contains an overabundance of potentially harmful mutations, which most likely led to reduced reproductive fitness and high rates of recessive disease in their population. There is evidence of this bottleneck event and its consequences in Neandertal fossils from the site of El Sidrón in Spain, where 13 closely related individuals exhibit evidence of 17 different skeletal birth defects.

Our species probably inherited some of these unfavorable genetic variants when our ancestors interbred with Neandertals tens of millennia ago. Is it possible that some of the harmful Neandertal-derived variants that have stuck around in our genomes now influence not only the sizes and shapes of some of our brain structures but also our propensity for neurodevelopmental and psychiatric conditions?

The accumulation of evidence to date suggests that this may well be happening. For instance, some Neandertal variants have been linked with the presence of major depression. Perhaps not coincidentally, these variants have also been implicated in determining chronotype—that is, whether someone is a morning or night person. Some scientists posit that the effects of Neandertal DNA on our chronotype, which is determined by our circadian rhythms, might predispose us toward depression because many mood disorders have a significant seasonal component (to wit: seasonal affective disorder, a type of mood disorder in which symptoms come and go with the changing of the seasons).

Neandertal DNA has also been associated with substance use such as drinking and smoking. Other genetic variants seem to increase pain sensitivity and prompt people to consume more pain medications. And a subset of Neandertal DNA variants may increase some people's likelihood of developing attention deficit hyperactivity disorder (ADHD), although these variants are slowly disappearing from the modern human genome.

One particularly intriguing connection that the two of us have been investigating is the possible link between Neandertal ancestry and autism. We first became interested in this link when we learned of the parallels between some of the brain con-

Neandertal DNA variants appear to be influencing development of autism in measurable ways across ethnicities.

nectivity patterns in visual- and social-processing pathways in nonautistic people who have more Neandertal DNA and people on the autism spectrum. People with autism often have enhanced visuospatial abilities—for instance, they tend to excel at picking out a target shape from a sea of distracting shapes in cognitive tests. At the same time, challenges with social cognition are typically central to the autistic experience and call to mind the reduced connectivity in those same neural pathways in nonautistic people with more Neandertal DNA. We also knew that just as Neandertals had smaller cerebellums than early modern humans did, which may have influenced their social cognitive abilities, people with autism consistently exhibit reduced volume in subregions of the cerebellum.

This wealth of data from genetics, neuroimaging and brain reconstruction prompted the two of us to question whether Neandertal DNA could be influencing autism susceptibility in modern human populations. Our laboratories set out to address this important question together, accessing genetic data on both autistic and nonautistic people from several large, well-established databases. We were also interested in looking at Neandertal DNA according to ethnic background because there is a lot of variability across modern populations. For instance, people of African ancestry tend to have less Neandertal DNA than Asian and European people. Thus, it was important to match our groups of autistic and nonautistic people according to ethnicity.

When studying Neandertal DNA in the modern human genome, scientists typically investigate single points in the DNA that vary across populations. These points of variation are known as single nucleotide polymorphisms (SNPs, pronounced "snips"). We were very interested in studying common and rare Neandertal SNPs separately because the rarer a DNA variant is, the more likely it is to be harmful and the less likely it is to be passed down to offspring. What we found was that autistic people tend to have more rare Neandertal SNPs than ethnically matched nonautistic people have. It's important to note that autistic people don't necessarily have more Neandertal DNA in general—they're not more "Neandertal" than the next person. It's just that the Neandertal DNA they carry includes more of the rare variants than nonautistic people tend to have.

We also investigated SNPs that specifically influence gene activity in the brain. We were able to identify 25 of these Neandertal-derived expression quantitative trait loci (eQTLs), as they are known, that were overrepresented in our autism groups. For example, about 80 percent of white Hispanic autistic males with epilepsy carried a particular Neandertal SNP in the *USP47* gene, compared with 15 percent of those in the nonautistic control group. Although the function of *USP47* is poorly understood, this gene has tentative links with epilepsy, which often co-occurs with autism.

In addition, we found a mutation in the *COX10* gene that occurred more frequently in Black people with autism than in Black people without autism. Animals genetically engineered so that their *COX10* is inactive tend to have a functional imbalance between the activity of excitatory neurons and inhibitory ones in the brain that is very characteristic of conditions like autism.

WE DON'T YET HAVE a clear idea of what all these Neandertal SNPs are doing in people with autism. They appear to be influencing development of the condition in measurable ways across all ethnicities studied. And our research suggests that many of the rare Neandertal-derived SNPs, which are associated with autism, help to orchestrate neural connectivity, which in turn may affect how neurons communicate with one another. But precisely how these variants are affecting brain development remains to be determined. In all likelihood, there is no single answer.

Genetics is an extremely complicated field of study. Although the human genome was sequenced more than 20 years ago, our understanding of molecular networks and how they influence organ development and function is still relatively rudimentary. As we dig deeper into how Neandertal DNA is influencing our genes, it is important to accept the complexity of the problem. There are more than 78,000 modern human genes that have mixed with nearly the same number of Neandertal genes. Humans can wrap their minds around a three-dimensional problem, but a 78,000D problem is rather more difficult! Fortunately, modern computers executing artificial-intelligence code can handle the analytical burden that our brains cannot.

Our initial study tagged Neandertal DNA in partial genome sequences that constitute just 1 percent or so of the entire human genome. In the next phase of our research we will scan recently available complete genome sequences from modern human families with a propensity for autism. By expanding our search area for ancient DNA from genes to regions *between* genes, we will be able to investigate millions of additional eQTLs, which regulate the intensity of gene expression much as a dimmer switch controls the amount of light coming from a bulb. Once we map these eQTLs to Neandertal-derived DNA variations in a modern human genome, we will be able to infer whether some Neandertal DNA is measurably altering gene expression.

A complete genome search will allow us to identify eQTLs from the Neandertal lineage that are involved in the function and development of not only the brain as a whole but also specific brain tissues and regions, such as the cerebellum. We may find that *H. sapiens* inherited entirely new neurodevelopmental traits from Neandertals that did not exist in our lineage until the two groups interbred. A more likely scenario, however, is that the introduction of Neandertal DNA into *H. sapiens* modified, but did not override or replace, genetic control mechanisms for extraordinarily complex brain conditions such as autism, ADHD and depression.

If we can identify the exact neurodevelopmental pathways controlled by mixed Neandertal/*H. sapiens* gene regulatory networks, we may be able to figure out how ancient DNA reconfigured gene expression in the brain at the point of hybridization. This type of knowledge would have a variety of potential therapeutic applications within the burgeoning field of personalized medicine.

We aren't interested only in Neandertal DNA. It may be that hybridization in general, not just DNA inherited from Nean-

Neandertals had a braincase that was long and low in shape (*left*), in contrast to the globular braincase of *Homo sapiens* (*right*). People today with higher percentages of Neandertal DNA are more likely to have an elongate skull reminiscent of Neandertals.

Philipp Gunz/MPI EVA Leipzig

dertals specifically, contributes to autism susceptibility—the result of a type of genetic mismatch, if you will. If that's the case, we might also expect to see DNA from other cousins, the Denisovans, who also interbred with early *H. sapiens,* playing roles in autism and other neurological conditions in ethnic groups of people today who carry Denisovan DNA (primarily people of Asian and Native American ancestry). We will be looking for signs of Denisovan influence in the next phase of our research.

LIKE THE ADHD-RELATED Neandertal variants that are gradually getting winnowed out of the modern human genome, the rare Neandertal variants that autistic people have may be getting weeded out of the gene pool, too. Some rare Neandertal DNA is probably fading away simply as a result of what population geneticists call the law of large numbers, which predicts that uncommon and rare DNA, regardless of its effects on the organism, will tend to slowly disappear from a large breeding population over time. But other Neandertal DNA may be rare because it is modestly harmful, affecting an individual's ability to have children and pass down their DNA.

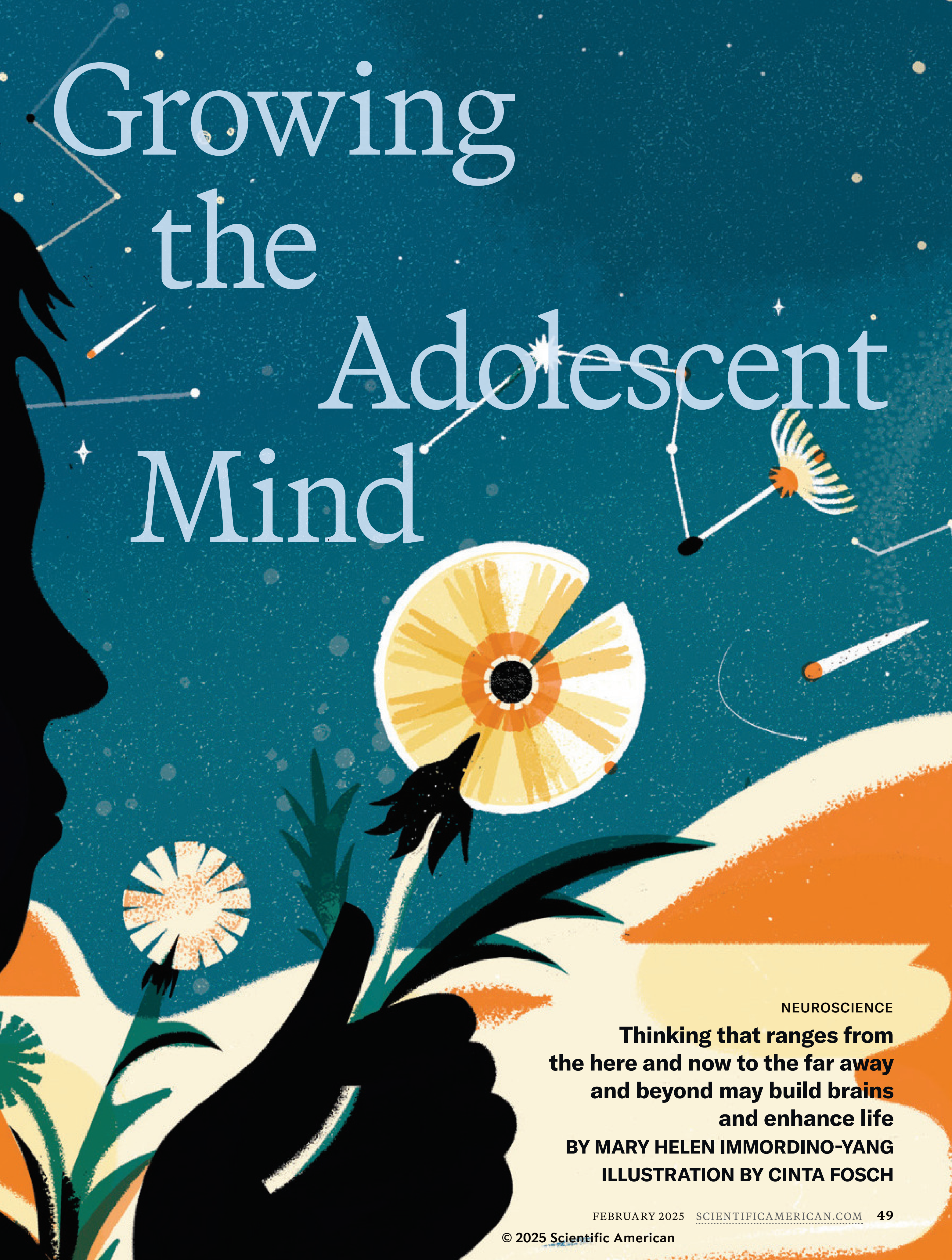
We know from research that, on average, people with autism are significantly less likely than the general population to have children, although there are certainly some who do have kids. But we don't know whether their reproductive rates are lower because people on the autism spectrum face challenges with romantic relationships or because they are more likely to have certain health-related disorders such as polycystic ovary syndrome that affect fertility. The answer is probably multifactorial. But regardless of the reasons, fewer offspring means fewer genetic variants associated with autism get passed down over time. So, if these variants aren't getting passed down as often, why are they still sticking around in the human genome, albeit in low numbers?

FROM OUR ARCHIVES
Human Hybrids. Michael F. Hammer; May 2013. Scientific American.com/archive

When it comes to autism, the medical community has traditionally focused on the deficits and challenges that people with the condition may experience. This approach is rooted in the medical model of disability, which in the case of neurodevelopmental differences holds that they should be treated medically with a focus on "fixing" or managing the condition and a goal of normalizing the person's behavior. But the autism spectrum is also associated with traits that may have been adaptive during more recent human brain evolution—enhanced visuospatial processing, high intelligence, exceptional memory and creativity, among others. Multiple genetics studies have found that many of the common genetic variants associated with autism are also associated with high intelligence, enhanced cognitive ability and educational attainment.

In addition, family members of people on the spectrum are more likely to have careers in fields related to science and technology and, according to our recent study, are also likely to carry some of these same rare Neandertal variants. Therefore, although autistic people have lower reproductive rates on average, their nonautistic (though potentially still neurodivergent) family members may also be helping to keep this DNA in the gene pool. In other words, even as some evolutionary factors are working to push these autism-related Neandertal-derived genetic variants out of the human genome, other factors are working to retain them.

Although we don't yet know whether the Neandertal DNA associated with autism is also linked to intelligence, savantism or general creativity, we are slowly connecting the dots. If such a relation exists, it suggests that intermixing with Neandertals has affected multiple aspects of brain evolution in our species. In this way, Neandertal DNA is not only a part of the story of autism and other neurodevelopmental and psychological conditions; it's central to the story of all of us. ●



Growing the Adolescent Mind

NEUROSCIENCE

Thinking that ranges from the here and now to the far away and beyond may build brains and enhance life

BY MARY HELEN IMMORDINO-YANG

ILLUSTRATION BY CINTA FOSCH

A THRILLING CRUSH, excruciating embarrassment or fervent dedication to a cause—adolescence can mean all of these things. For me, it involved a burning curiosity about the natural world, which led one time to my grandmother discovering a bag of cow eyeballs in the fridge. My dad had helped me collect them at a slaughterhouse for dissection.

I didn't mean to upset anyone; I just wanted to figure out how sight works. Like others my age, I was also driven to understand why things are the way they are and how they could or should be different. A while after my eyeball phase, I declared myself a humanist and took to wearing a four-inch peace sign around my neck. My sister and I began writing and performing (admittedly somewhat histrionic) folk songs through which we attempted to express our discontent with various global, local and historical injustices.

As a teen, I was swimming in big ocean waves, so to speak—watching, listening, questioning and grappling to make sense of all the complex cultural and emotional information coming my way. Who are we humans, anyway, and who am I? Now, 35 years later, I am still fascinated by these questions and by the ways in which adolescents struggle to make sense of what they witness and experience.

Take these responses from teens in urban Los Angeles to my asking them why they think some people in their neighborhood commit violent crimes:

> "They have, like, a lot of emotions. They're really mad, so they just kill somebody. Like, overly aggressive."

> "Everyone has a history. Like, everybody has an action or choice or some sort of history—some sort of thing happened to them that affects how they act in the future."

The difference between the quotes is subtle but critical in its implications for brain development. The first one describes the proximal reason for a crime and represents the kind of focused thinking people need to keep themselves safe and to respond appropriately to shifting circumstances. But the second reveals awareness of the broader historical, cultural or social context in which individuals do the things they do.

Every adolescent I have worked with, irrespective of IQ score or social or economic background, has the capacity for such mental time travel. By listening closely to teenagers' reflections and observing their brain activations as they lay in a neuroimaging scanner, my colleagues and I discovered that thinking that ranges flexibly from the here and now, as in the first quote, to the past, the future and everywhere else, as in the second, seems to literally build their brains. During such wide-ranging, emotionally powerful, reflective thinking—which we call transcendent because it soars beyond the moment—key brain networks activated and deactivated in complex, dynamic patterns, which, our data indicated, grew and strengthened their connections.

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This emerging capacity to muse in abstract ways enables teenagers to understand themselves, their family, friends and society at large and to imagine what their own place in the world might be. Over time such transcendent thinking constructs resilience to adversity and places young people on a path to future satisfaction with life, work and relationships. Our research helps to explain why adolescents can be among society's most visionary and idealistic citizens (and, alternatively, some of its most self-absorbed) and shows that to truly empower their growth, parents, schools and communities need to focus less on what kids know and more on how they think.

> **Reflective, emotionally powerful thinking—which we call transcendent—may literally build brains.**

IN THE MID-2000s, when I started studying neuroscience, many researchers thought of adolescence in terms of its deficits. Neuroimaging studies were establishing that although the brain's centers for automatic emotive reactions, such as the amygdala, develop early, the prefrontal cortex, involved in measured and rational thought, is not mature until a person is in more like their mid-20s. Such findings persuaded neuroscientists such as BJ Casey of Columbia University to argue that adolescents are not only less knowledgeable than adults but also less emotionally stable and not fully responsible for their actions. "A skeetering top, nearly gyrating out of control," is how neuroscientist Robert M. Sapolsky of Stanford University described the teen brain in his 2017 book, *Behave*. In this view, adolescents' transformation into mature adults requires not only amassing knowledge and skills but also developing self-control to curb their appetite for risk and to rein in their strong emotions and sensitivities.

That teenagers' passions are also crucial to their learning was clear to me even as a 23-year-old science teacher in a public junior-senior high school south of Boston. Being interested not only in nature but also in how nature produces culture, I had by then lived with families in France, Russia, Ireland and Kenya, imbibing their languages and daily activities. After returning to the U.S., I had majored in French literature in college while taking every science course I could. I also loved building things, but when a cut in my hand meant giving up my postgraduate job as an apprentice carpenter, I somehow convinced the Massachusetts Board of Education to give me a chance at teaching seventh-grade science.

The public school I taught in was immensely diverse, with 81 languages spoken among the students. Many were first-generation immigrants and refugees, who landed in my class like deer in headlights. The mostly 13-year-olds were intensely curious about the differences in their appearance and customs.

One time, after a lesson on human evolution in which I'd shown a video depicting how early East African hominids might have lived, a Black girl I will call Marila put up her hand. Marila was a strong student, but she was clearly nervous, and I could see she was being egged on by her classmates to ask her question: "Ms. Immordino, why is it that when we're studying human evolution, they always show these creatures in Africa with dark skin? Why do they always look like Black people?"

"Because they live on the equator," I responded. "The sun is very strong there. Your skin would burn and you'd get skin cancer if you didn't have a lot of melanin to protect you."

There was a stunned silence. That silence evolved into a fervent class discussion that went on for months. The students were using the science they learned in the classroom to figure out who they were in the world. That got me hooked. Why had they interpreted the lesson in such a personal, emotional way? And why, long after the classroom turbulence had settled, did so many of my students suddenly seem to take a new interest in science?

I began to study developmental cognitive neuroscience at night school and eventually enrolled in graduate school at Harvard University in 1997. As early as the 1930s, I learned, naturalist-turned-psychologist Jean Piaget had observed that at about 11 or 12 years of age, children begin to think abstractly about issues such as morality and to ponder complex scenarios. Psychologist Erik Erikson noted two decades later that adolescents reflect on their values and beliefs to figure out who they are and how they fit in with everyone else. These and a succession of other scholars, such as Richard Lerner of Tufts University, William Damon of Stanford and Kurt W. Fischer of Harvard, characterized adolescence as a period of emerging capacities for abstract thinking that, together with heightened social sensitivity and a propensity for strong emotion, enable teenagers to infer overarching principles or hidden personal lessons from specific experiences or events. Adolescents seem almost compelled to look for these connections and their deeper meaning, as I had seen in my Boston classroom.

After graduating in 2005, I had the immense good fortune to begin a postdoctoral fellowship supervised by neuroscientist Antonio Damasio, who had just moved to the University of Southern California with his colleague and spouse, Hanna Damasio. Through decades of clinical research the Damasios had proposed something radical for the time: emotions, rather than interfering with clear-headed thinking, *drive* clear-headed thinking—thinking that is rational, responsive to circumstances and morally aware.

One patient known as EVR demonstrated this insight particularly well. He'd been a smart and successful businessman, happily married and raising a family. After he had surgery for a brain tumor, however, things changed. The operation involved removing parts of the lower surface of his brain's frontal lobes, just above and behind his eyes. When EVR returned to work, he started making shortsighted business decisions—which resulted in predictable bankruptcy. He began offending those he loved most and seemed callous about their pain, apparently incapable of remorse or embarrassment. EVR divorced his wife, remarried and quickly divorced again.

Through exquisitely thoughtful studies, the Damasios and their colleagues demonstrated that although EVR's IQ continued to test very high after the surgery, his brain had a deficit that was preventing him from using his intelligence ethically or advantageously. He acted in antisocial ways and made decisions that to any healthy person would seem irrational. And he was strikingly unable to learn from his mistakes. EVR knew the right things and had the necessary memories to guide him, but he was unable to care about the implications of his decisions. The Damasios came to under-

Adolescents' transcendent thinking may help key brain networks come to communicate more efficiently.

stand that EVR's emotions were not properly informing his planning and cognition, and his social relationships suffered for it.

On my first day at USC, Antonio came to my office. "I'd like to study social emotions," I recall him saying as we sipped Italian espresso. "I want to understand how the brain feels emotions like compassion, admiration for virtue, and contempt—emotions that form the basis of human morality, creativity, culture and the arts. Emotions that are the hallmark of acculturation and education. No one has yet done this. Are you interested?"

That day marked the start of a long journey—one that would integrate the insights I had gained from my adolescent pursuits, my travels, my seventh graders, my Harvard professors, the Damasios and other colleagues, and, eventually, my own students and my work with them. It would lead me to a new way of studying adolescent thinking.

AT THAT TIME, advances in functional magnetic resonance imaging (fMRI), which maps blood flow in the brain, were enabling neuroscientists to track which regions activate and deactivate during different states of mind. It was becoming possible to detect emotions' traces in the brain—not only the signs of basic emotions, like fear of heights or disgust over spoiled food, but also those of "social" emotions, which pertain to oneself, to cultural ideas and artifacts, and to the social world.

An early surprise from the fMRI studies was that even when someone rested idly in the scanner, key regions of their brain were activating in a coordinated way. Some of these areas are among the body's most metabolically expensive tissues, sucking up more glucose and oxygen than even muscle tissue. Why would such labor- intensive regions be activated during rest? The answer, it turns out, is that free-form, reflective thinking is extraordinarily important.

In 2001 neuroscientist Marcus E. Raichle of the Washington University School of Medicine in St. Louis and his colleagues described the default mode network (DMN), a set of regions mainly in the core of the brain that we now know are key to one's sense of self. The DMN is active when someone is daydreaming, recalling a meaningful incident from the past or trying to comprehend a complex issue. Many studies since have shown that the DMN also helps us to feel compassion, gratitude, admiration or awe and to perform feats of imagination or creativity. When we aren't focusing on the outside world, we aren't idle after all—we are conjuring stories, beliefs and imagined futures, traveling through time and possibilities to invent ideas and derive meaning from our experiences.

The DMN quiets down during focused, goal-driven activities such as filling out a tax form or catching a ball. That's when the executive control network (ECN) comes online to keep you on task and attentive. In the late 2000s William W. Seeley of the University of California, San Francisco, Lucina Uddin of the University of California, Los Angeles, and others identified a third network, the salience network (SN). It links regions that sense internal body states and tells you, for instance, when you have a stomachache. The SN is also involved in the kind of arousal you might experience when you see a snake in your path, notice that a song you like is playing or realize you've made an error in the math problem you're solving.

After some trial and error, I settled on a remarkably simple experimental paradigm. We shared short documentary-style stories with participants, first in a private interview and then again while they lay in the fMRI scanner. By comparing individuals' psychological responses when discussing their feelings with the neural activity patterns they showed in the scanner, we began linking people's feelings and ways of thinking about the world to underlying neurobiological mechanisms. Our first paper, published in 2009, reported something quite profound.

When participants told us from within the scanner that they felt deeply moved by the real-life stories we were sharing with them, we saw activation in the brain stem, which operates far below conscious awareness and is necessary for consciousness and physiological mechanisms of survival such as your heart rate. We also saw excitation in the insulae, regions of the SN that sense internal bodily signals, like when your heart is pounding from exercise, love or fear, and in the anterior cingulate cortex, a hub of brain connectivity important for emotion, motivation and learning. And we saw activation in the DMN's posteromedial cortices—extensive regions in the middle of the back of the head that relate to states of consciousness, such as when someone passes from light to deep anesthesia.

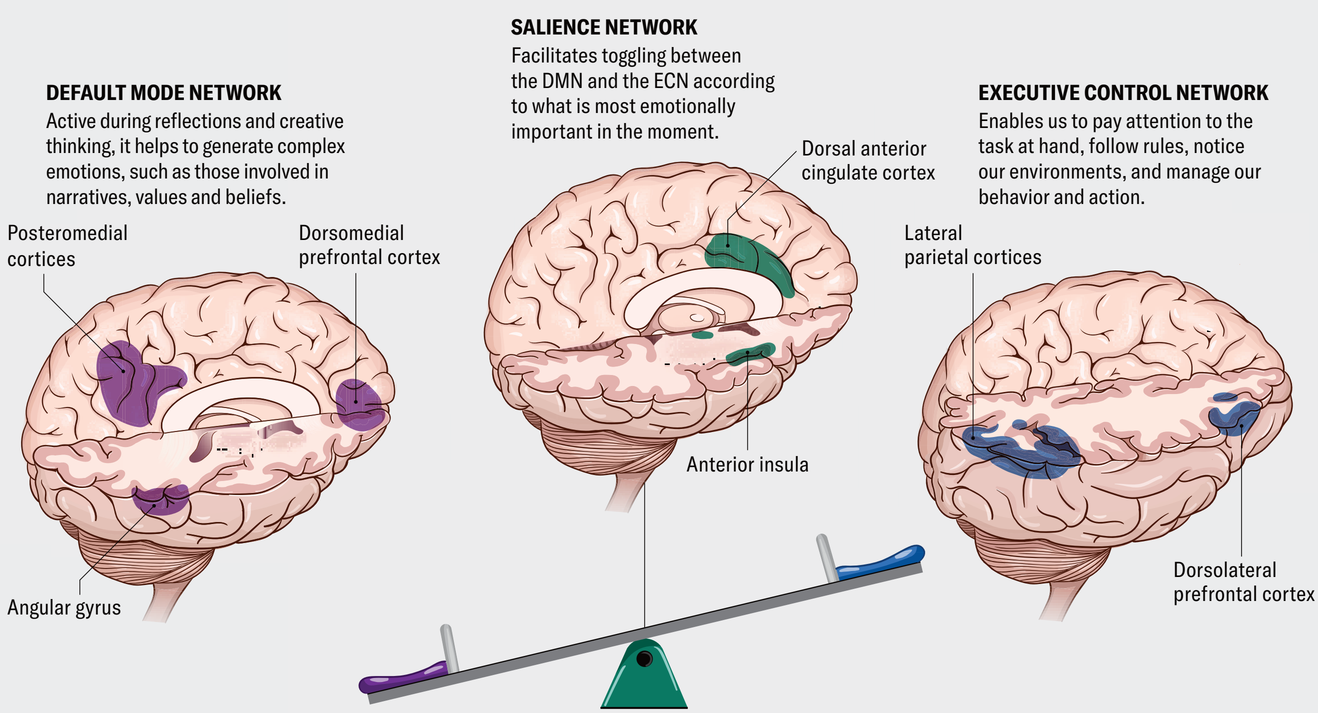
In sum, we demonstrated what the Damasios and others had previously hypothesized: social emotions such as admiration and compassion—which require complex inferences about others' experiences, intentions, beliefs, values, stories, histories and imagined futures—recruit many of the same brain systems that keep us alive. The SN not only senses bodily signals, it is also important for feelings of all kinds, including feelings of personal agency. It makes whatever you are thinking about seem relevant, pleasing, beautiful, painful, repulsive, interesting or urgent. It gives you a jolt when you notice something you care about. And it contributes to decision-making and cognition—weighing the relevance and urgency of information to prompt shifts between different modes of thinking.

We now know the hormonal surge associated with puberty not only escalates emotions, imbuing ideas and encounters with deep meaning, but also launches a critical period of malleability in brain networks, including the DMN, ECN and SN. Teenagers respond powerfully to social and other cues, which drive key networks to reorganize in response to experiences. This protracted period of brain development enables us to adapt effectively to a staggering diversity of physical and social environments—from the equator to the Arctic and from hunter-gatherer bands to cities of millions. It is essential to being human.

OVER YEARS of experiments and theorizing, I went on to probe how complex social emotions work in the brain, eventually launching my own lab in 2014. Through a series of studies in Beijing and Los Angeles, my student Xaio-Fei Yang (no relation) and I documented how culture influences the brain processes by which people experience social emotions, such as admi-

Networks for Transcendent Thinking

Three major networks of brain regions are important for many aspects of psychological functioning. The default mode network (DMN) is internally focused and reflective; it helps us build a sense of self. The executive control network (ECN) is more outwardly focused and enables attention to specific goals. The salience network (SN) constructs feelings of all kinds, weighing their relevance and urgency to shift thinking between the DMN and the ECN. Transcendent thinking, which ranges flexibly across these networks, appears to strengthen connections between the DMN and ECN and to enhance well-being.



ration and compassion. With Darby Saxbe, then a postdoc, we showed that individuals vary in their brain responses when feeling social emotions and that their ways of talking in an interview could predict these styles of neural processing.

Working with local teenagers and a succession of brilliant undergraduates made me wonder how the messy brew of hormones and new capacities for social and emotional abstract thinking might come together in the brains of adolescents. That emotional processing varies across individuals and is shaped by culture, as we had shown, suggested that individuals at least partially *learn* how to have complex emotional experiences—and that we could capture this learning with interviews paired with fMRI imaging. With my student Rebecca Gotlieb, Yang and others, I eventually launched an ambitious project to look at how teens' ways of making meaning are related to brain mechanisms—and how these thought patterns might drive changes to their brains over time.

In 2012 my team recruited 65 students between ages 14 and 18 from public high schools serving diverse and low-income urban communities in Los Angeles for a long-running study of thinking and brain development. These youths, we reasoned, were particularly likely to be facing complex challenges and may have been uniquely placed to notice the intricacies of their social milieu. We showed them videos of true stories about teenagers from all over the world and interviewed them about their responses. We also gave the adolescents three types of brain scans later that day and again two years later, following up with online questionnaires and phone conversations over the next three years as most of them entered their early 20s.

All the adolescents talked at least a bit about the bigger picture—the lessons they took from a story, especially if it felt poignant. For example, I showed Isela, a participating teen, a video of Malala Yousafzai filmed when she was a 12-year-old in Pakistan determined to continue studying despite the Taliban having forbidden it. I asked Isela how it made her feel. She responded:

> "Um, this story makes me feel upset—how she wants to be a doctor and continue on with her education, but it makes her sad … knowing her journey would be very difficult."

I nodded, and after pausing for a few moments, Isela went on:

> "And it's crazy how it's that powerful.… I mean… it makes me think about my own journey in education and how I want to go to college and hopefully be a scientist someday. And even more, I guess what really hits me is how not everyone is able to get this chance, to go forward with their life and get an education or do what they want to do with their life. I mean, it's not right."

Again, Isela stopped to think. Her gaze

Graphic by Ni-ka Ford

> In people with mood disorders, the mind may be less able to flexibly shift between different modes of thinking.

wandered from the image of Malala on the computer screen in front of her to the tree outside the window by my desk. Then she turned back to me and continued:

> "Ah, I guess when I think more, yeah, it makes me feel upset that, um, others live in certain parts of the world where they don't want people to learn and they are trying to, like, hold them back. But then, uh, her story, like, inspires me to work harder so that, uh, I can prevent those things from happening maybe. Everyone everywhere should have the chance… I mean, all human beings should be able to live free and choose their life future."

After reacting empathically to the concrete details of Malala's situation, Isela went beyond these details to consider the personal and ethical implications of the story. All the teens *could* think transcendently, we found, but some, like Isela, did so far more than others. After the interview, we asked each student to rest in an fMRI scanner for about 10 minutes so we could evaluate the cross talk among their brain networks. We also conducted so-called diffusion tensor imaging, which allowed us to measure changes to the brain's white matter fiber tracts, the routes by which distant regions of the brain communicate. Finally, we obtained high-definition images of their brain tissues to assess the volume of different regions.

As an analogy, if we were to think of the brain as a country, the fMRI scans measure how lively each city is and how much travel or communication there is between cities; the diffusion tensor imaging evaluates the quality of the roads; and the high-definition structural images assess the quality of each city's infrastructure. Putting these measures together, we got a consistent picture of brain change over time—and found that this change was predicted by teens' tendency toward transcendent thinking in the original interview.

The stories we shared with the teens were compelling. To what extent were the adolescents motivated to figure out the deeper meaning of what they had learned? The more they grappled with the bigger questions, we found, the greater the increase in coordination between the ECN and the DMN over the two years between the fMRI scans. This finding suggested that adolescents' propensity for transcendent thinking might have helped these key networks to communicate more efficiently over time.

As Isela and other teens went about their lives, they would have brought this propensity with them, making the time and effort to think about what they were seeing, feeling and learning and thereby exercising the connections between the networks. Further, more transcendent thinking also meant greater enhancement of the robustness of the fiber tracts connecting the networks of the brain in the two years between the first and the second brain scans.

Also important, in many key regions of the brain, particularly in network hubs in the SN and frontal lobes, we found that more transcendent thinking in the original interview counteracted age-related thinning of the cerebral cortex over time. In a classic 1999 study, Jay Giedd of the University of California, San Diego, and his colleagues discovered this pattern of thinning by comparing brain development in individuals age four to 20. This thinning is thought to reflect increased efficiency of the brain as unused circuits are pruned. Research is now showing the story is more complicated because when the thinning is slowed, it is associated with less stress and higher intelligence. It is interesting that in about half of our teens, transcendent thinking even predicted increases in cortical volume—it apparently caused their brain to grow even more than normal pruning shrank it.

The more teens grappled with the bigger picture and tried to learn larger lessons from the stories, the more they developed their brain over the next two years. Transcendent thinking appears to enhance communication between the DMN and the ECN, to slow the loss of gray matter and to even physically build the brain. This multifaceted brain growth, in turn, predicted greater identity development, measured as the degree to which a teen reported thinking about who they are and what they stand for, as per the original work by Erikson. (In contrast, teens who say they "just hang with the crowd" and "rarely try things on their own" are not likely to have a strong sense of self.) Most significant, these findings had no correlation with the teens' IQs, which we measured, or with their family's financial means or parents' education levels. Nor did they differ by gender or ethnic group.

As young adults, about five years after their first interview and brain scan, youths who had evinced more transcendent thinking and brain growth also reported greater life satisfaction—for example, by saying they liked the person they had become. We had discovered something quite fundamental: a teen's proclivity to expend effort on deep thinking and meaning making may itself be a source of brain development that supports well-being.

OUR FINDINGS are also synergistic with recent research in adolescent mental health, which ongoing clinical research is associating with the same networks whose development we found to be supported by transcendent thinking. One study led by Caterina Stamoulis of Harvard University recently reported that adolescents with less robustly connected brain circuits were more vulnerable to the emotional effects of pandemic stressors, for example. Another study using the same large-scale, long-term data, led by Patricia Kuhl of the University of Washington, showed that the stress of the pandemic was associated with increased and earlier thinning of the cortex among teens. The relations between these findings and ours are complex and nuanced, but on the whole they suggest that transcendent thinking promotes patterns of structural growth in the cortex and network connectivity that are associated with resilience.

What may be happening in people with mood disorders is that the mind is less able to flexibly shift between different modes of thinking. (This idea has been the core of child psychiatrist Dan Siegel's theory of "integration" of the mind for mental health for more than a quarter of a century, and it echoes Vinod Menon's "triple network" model of brain function in psychiatry, involving the SN, DMN and ECN.) The mind might be so focused on dealing with tasks or threats that it gets stuck in executive-control mode, worrying or working compulsively, which occurs with anxiety, or in default mode, characterized by brooding and being unable to act in a goal-driven way, which marks depression. In contrast, young people who can tap into different brain networks in an organized way, according to what should be salient at that time, may be better able to manage their attention, imagine themselves in others' situations, and have overall better relationships and quality of life.

When our teen participants were at the lab, we also asked them to report any violent acts they had witnessed or heard about in their community and then interviewed them about their understanding of the causes of and possible solutions to such social problems. Consistent with brain studies of soldiers deployed to war and individuals suffering from post-traumatic stress disorder, exposure to violence in our teens was associated with thinning of a key brain region in the SN, the anterior middle cingulate cortex (ACC), which is involved in pain processing, motivation and learning. Hearteningly, however, we also found that teens who reflected more on the broader historical, cultural or social context of the crimes they had witnessed, rather than simply blaming the implicated individuals' bad behavior in that moment—in other words, teens who thought more transcendently about this civic issue—showed a protective effect. The more transcendent thinking these teens engaged in, the less thinning we found in the ACC.

Ultimately we believe that transcendent thinking may be to the adolescent mind and brain what exercise is to the body: most people can exercise, but only those who do will reap the benefits. We believe that teens who showed more transcendent thinking in our interviews were going about their daily lives with more curiosity and thoughtfulness and using their strong emotions to propel this thinking rather than engaging in superficial and reactive thinking. Our study underscores the role teens play in their own brain development when they make deeper meaning of the social world.

What does this mean for society? Our schools tend to be preoccupied with what students know and can do, and parents are focused on helping their kids succeed in this outcome-oriented system. It is true that teens need rich, relevant content to learn about and that students' hard work in school will be important for their future opportunities. But our studies add to a growing body of research suggesting that our ultimate focus should be on how teens think and feel. What good is it to know algebra, for example, if you have no inclination to use it when making financial decisions? What use is knowing about the U.S. Civil War if you have no capacity to think deeply about the ethics and motivations of that conflict and how that history shaped our modern societal landscape, values and institutions? Why learn science if you cannot use that approach to discern fake from evidence-based recommendations during the next pandemic?

These findings make me realize how my upbringing shaped me. My parents were city people, but they decided they would raise their kids in the middle of the woods in Connecticut. A clearing formed when a hurricane ripped out trees became a pasture for the animals we raised and ate, and the fallen trees became boards with which we built a barn and fences. I ran around in the woods with my siblings, friends and dogs; rode horses and taught neighborhood kids how to ride; helped a sheep give birth and dissected the placenta; and never saw a house key until I reached college. I sometimes found it difficult to navigate between the structure of school and the freedom to explore I had at home. But as an adult looking back, I can see how the opportunities I had to follow my interests prepared me to engage in both focused and open-ended thinking and to pursue my curiosities relentlessly.

In 2019, to focus on these issues, I founded USC's Center for Affective Neuroscience, Development and Education (CANDLE). Our team is particularly interested in adolescents' curiosity and willingness to consider multiple perspectives, big ideas and broad implications, as well as in the ways teachers and schools can support these processes. Teenagers are eager to sink their teeth into complex, interesting content that invites them to explore big, emotionally powerful ideas. Innovative school designs and teaching practices can engage students in choosing and pursuing open-ended, project-based coursework, leveraging their interests to broaden exposure to new knowledge, concepts, skills and questions. Such schools support their students by encouraging them to make sense of all they are discovering through writing, problem-solving, dialogue and reflection.

FROM OUR ARCHIVES
Age of Opportunity. Lydia Denworth; May 2021. ScientificAmerican.com/archive

In New York State's performance-based assessment schools, for example, classes culminate in students presenting the things they have learned to panels of teachers, evaluators, and other students. This approach, rather than focusing on testing, is designed to enable students to recognize the importance—the salience—of academic content. It then helps these newly motivated students shift between a tight focus on skills and information and the effortful but often inspiring reflections that connect the work to big ideas.

Here's how a student at one of these schools, who had never before passed a math class, described his project to solve Zeno's paradox, in which a person walks progressively toward a door in front of them, halving the distance with each forward movement but never quite reaching the destination:

> "I want to be the first person in my family to graduate from college ... [but] I never even imagined I could reach that level of math. My school has helped me learn mathematically, learn how to think outside the box, in different strategies .... I have spent two months working on a problem called 'walking to the door'... It led me to think about limits and the idea of asymptotes. I had to study fractions to be able to think about the problem I had. Through doing the problem, I got fascinated by finite and infinite. I was able to connect it to my life."

Think about it—he connected Zeno's paradox to his *life.* Given support for specific skills as he needed it, this student felt empowered to explore a challenging math problem that ended up feeling personally compelling, maybe because as he shifted between focusing on the math (recruiting his ECN) and musing on the big ideas (invoking the DMN), he fired up his SN—that brain network that makes something "feel like me."

In transcendent thinking, teens rally their knowledge and skills and their strong capacity for emotion to imbue their worlds with meaning. For a while they let go of appearances and tasks and settle into a mental space where they are safe to explore ideas and, in the process, build purpose and meaning. In that space, they invent possible worlds and selves, grapple with alternatives and perspectives, and conjure the understandings, ethics and narratives that will carry them, and us, forward. ●

Redefining Alzheimer's

NEUROLOGY

According to new expert recommendations, the disease can be diagnosed after detection of its underlying biology, even before the onset of cognitive decline

BY LAURA HERCHER

ILLUSTRATION BY XINYUE CHEN

I

T IS IMPOSSIBLE, OF COURSE, to identify the precise moment we first suspected the changes in my mother were something other than normal aging. In my own imperfect memory, what rises up is the first morning of a weeklong trip to Rome, when my mother woke up at 2 A.M., got dressed and went down for breakfast. A hotel employee found her wandering from room to room, looking for toast and coffee. She was jet-lagged, my brother and I told each other uneasily. It could happen to anyone. But weren't there cues? Didn't she notice the darkened lobby, the stillness, the clock?

Laura Hercher is a genetic counselor and director of student research at the Joan H. Marks Graduate Program in Human Genetics at Sarah Lawrence College. She has written broadly on ethical, legal and social issues related to genetic medicine. Hercher is host of *The Beagle Has Landed*, a podcast for the clinical genetics community and other sci-curious individuals.

If we had known then, would it have helped? To date, no U.S. Food and Drug Administration–approved therapy exists for asymptomatic people at risk of Alzheimer's disease (AD). My mother was not a smoker, drank in moderation, read books, took classes, and spent that week in Italy soaking up everything the tour guide told her about Caravaggio and Bernini like she was prepping for a quiz.

Five years passed after that trip before my mother received a diagnosis of dementia. Today, a simple blood test can detect changes in the brain that predict AD up to 15 years before the first symptoms emerge. For researchers, tools for early detection give a peek at the full spectrum of AD, pinpointing early seeds of pathology deep inside the brain. Cognitive decline—what we typically think of as the disease itself—is merely the illness's denouement. "Dementia is a result. Dementia is a symptom," explains Clifford R. Jack, Jr., a neuroradiologist at the Mayo Clinic in Rochester, Minn., and chair of the Alzheimer's Association (AA) working group responsible for recent, controversial guidelines for the diagnosis of AD based on underlying biology, not clinical presentation.

Biomarkers for AD—signs of the physical changes in the brain that contribute to disease progression—have been known for more than two decades. In 2007 an international working group (IWG) of dementia experts described biomarkers as supporting evidence for a diagnosis of the disease, defined at that point largely as it was by neuropathologist Alois Alzheimer in 1906: progressive memory loss, confusion and personality changes caused by distinctive plaques and tangles in the brain. For almost a century, those brain changes could be confirmed only on autopsy. While the affected person was alive, the label was merely presumptive. In fact, postmortem studies have found that up to 30 percent of people who received a clinical diagnosis of AD did not have the characteristic plaques and tangles.

Does it matter what caused a person's incurable dementia if the result is ultimately the same? Yes, for many reasons, it does. A lack of specificity means affected people and their families receive less accurate information about disease prognosis, as well as about the risk of the same condition occurring in other relatives. And it stymies researchers, whose study populations are a confounding mix of true and false positives. "Can you imagine a clinical trial for cancer where a third of the people didn't have cancer?" Jack asks.

INCORPORATING BIOMARKERS into clinical care was envisioned as a way of reducing uncertainty in the diagnosis of AD. But in 2018 a group sponsored jointly by the AA and the U.S. National Institute on Aging made a more radical proposal: biomarkers didn't confirm a diagnosis of AD; they *were* a diagnosis of AD. Under this paradigm, AD, a condition characterized by abnormal protein deposits in the brain, is a disease that begins with an asymptomatic phase and progresses—if the patient lives long enough—to mild cognitive impairment (MCI) and, eventually, a level of dementia that interferes with the processes of daily living.

For researchers, it was helpful to reconceptualize the disease as a continuum with distinct stages that correspond to physiological changes in the brain. As Bruno Dubois, a professor of neurology at Pitié-Salpêtrière University Hospital in Paris and a leading member of the IWG, wrote in a paper published in 2018, "considering AD only at a dementia stage is detrimental to care for patients affected by the disease." Dementia, he argued, was evidence of damage that was already beyond repair; identifying people earlier opened the door to preventive care—were that to exist—and created a valuable pool of candidates for research. For this reason, and to clarify that the recommendations were not intended for general clinical practice, the 2018 guidelines were designated a "research framework."

Since 2018 two fundamental new developments have changed the stakes for early diagnosis. The first was the arrival of "disease-modifying" treatments—not cures but drugs that slow the course of AD. Lecanemab, approved by the FDA in July 2023 for people with MCI or mild dementia, is given by infusion every two weeks and has been shown to reduce disease progression by 27 percent. Its effectiveness in the later stages of the disease, as well as in asymptomatic people, is unproven. Donanemab, approved by the FDA almost exactly one year later, is a monthly infusion with a similar side-effect profile and comparable effectiveness.

The second advance was the potential to make testing more accessible because of blood-based biomarkers. In 2018, Jack explains, "biologically based diagnosis either required a PET [positron-emission tomography] scan, which is obviously expensive and not widely available, or required a lumbar puncture for cerebral spinal fluid—again, invasive." A simple, inexpensive and highly accurate blood test that can be done anywhere has greatly expanded the possibilities for biomarker testing in routine clinical care. In 2023 the AA convened another working group, chaired by Jack, to revisit the 2018 criteria. The updated recommendations, which were published last June, double down on the idea of biomarkers as diagnostic.

Because there are currently no validated treatments for those who have biomarkers but not symptoms, the new guidelines discourage testing asymptomatic people except in the context of research. But clinical trials of lecanemab and donanemab for biomarker-positive asymptomatic people are underway—and the study authors clearly envision a time when presymptomatic testing will be routine. "The point is," Jack explains, "we're setting the stage for the future when there are approved treatments that have been proved to lessen developing impairment in people who are now cognitively unimpaired."

Under the new proposal—now a "clinical framework" rather than a "research framework"—it is not inconceivable that someday soon a person will walk into an annual physical feeling perfectly healthy and leave with a diagnosis of AD. In Jack's view, that is a

Today a simple blood test can predict Alzheimer's 15 years before the first symptoms.

matter of empowering patients. "Paternalism in medicine is a bad idea," he insists. "Tell people the truth, and educate people on what it means." In some future universe, those diagnosed might be offered a simple pill or other treatment to delay or prevent dementia altogether. "That," Jack says, "is the holy grail."

Other groups, including the IWG of dementia experts and the American Geriatrics Society, disagree vehemently on this use of the word "diagnosis." The introduction of biomarkers made the disease a "clinical-biological entity," Dubois explains. But in his view, no one without symptoms should be diagnosed on the basis of biomarkers alone. "Both are necessary," Dubois adds. In new recommendations presented in November 2024, the IWG argues that "disclosing a diagnosis of AD to cognitively normal people with only ... AD biomarkers represents the most problematic implication of a purely biological definition of the disease."

THE DIFFERENCE BETWEEN "diagnosed" and "at risk" might seem semantic, but the word "diagnosis" has significant real-world implications. It carries weight with clinicians and insurance companies, increasing the likelihood that therapeutics will be prescribed and covered. This can be a good thing, but it also can be a problem. As one of the commenters on the second draft of the 2024 diagnostic criteria pointed out, a substantial number of the people diagnosed with AD under these criteria will die without ever having exhibited signs of dementia.

The possibility of developing a screening test to identify presymptomatic AD merits our attention, but, the commenter added, screening programs elsewhere in medicine have shown mixed results: some "have yielded clear benefits and little harm to individuals, [whereas] other efforts have resulted in wasted resources and even potential harm." Both outcomes are possible consequences of the expanded use of lecanemab and donanemab, which cost $26,500 and $32,000 per year, respectively, and come with a side-effect profile that includes a risk of swelling and bleeding in the brain.

Using biomarkers for AD as a basis for diagnosis rather than risk assessment also raises questions about how this information will be received by those who are diagnosed. Is it burdensome to live with the knowledge that you are at risk for dementia? This question is familiar to geneticists, who have been wrestling with it since testing became available for genes associated with AD more than two decades ago.

These genes generally fall into two categories. Mutations in three genes cause an early-onset version of AD, with signs of dementia generally in evidence by age 55. Collectively, these rare mutations account for less than 1 percent of people with AD, and they are deterministic in a way that is atypical for genetics. If you have one of these mutations, it is a virtual certainty that you will develop symptomatic AD by age 55. Given this stark reality, it was understood that finding out you carried one of these mutations could be traumatic, and genetics professionals developed a protocol to help people decide whether they wanted to test for the genes and to help them cope with the result.

The other group consists of susceptibility genes, principally *APOE,* which has a profound but still incremental effect on the risk of AD. Carriers of a single copy of a certain version of the gene, *APOE* ε4, are two to three times more likely than the general population to get AD by age 85. Dosage creates a multiplier effect: people who inherit *APOE* ε4 from both of their parents are 12 times more likely to get the disease. These individuals, called *APOE* ε4 homozygotes, have a 60 percent chance of developing AD by age 85. And this gene variant, unlike its more deterministic cousins, is not all that rare; 2 percent of people in the U.S. are *APOE* ε4 homozygotes.

Robert C. Green, a medical geneticist at Harvard Medical School who led a series of trials examining the impact of disclosing *APOE* AD risk to asymptomatic adults, recalls the uncertainty that swirled around the issue of *APOE* testing in the early 2000s. "We didn't know what percentage among families would want this," he says. "And most important, we didn't know whether we would be creating catastrophic distress in those family members if we disclosed a risk factor for a then—as now—untreatable condition." This decades-long effort, called the Risk Evaluation and Education for Alzheimer's Disease (REVEAL) study, established that many but not all people wanted the information—and that although it was of course upsetting for those who tested positive for *APOE* ε4, people could handle it. In fact, Green says, those who chose to participate in the study reported that getting their *APOE* results had "personal utility." "They actually did things with the information that were important to them," he says. "They purchased a different kind of insurance. They had conversations with their family. They at least considered making changes in their career planning."

A key element in the REVEAL messaging, however, was that *APOE* is not deterministic. Now some researchers are making the argument that two copies of *APOE* ε4 equal a diagnosis of AD, potentially muddling that message. According to Jack, under the 2024 AA criteria, *APOE* ε4 homozygosity, like a mutation in an early-onset AD gene, is considered a "stage 0 diagnosis." This logic reflects the fact that people with these gene variants are born with a condition that, in all likelihood, affects processes in their brain throughout their lifetime; it does not mean they will necessarily get dementia, and many will not.

A similar conclusion was reached by the authors of a large study that compared genotype with biomarkers and postmortem investigations of the brain, led by neurologist Juan Fortea, director of the Sant Pau Memory Unit in Barcelona. In a paper published in May 2024, they presented evidence that almost all *APOE* ε4 homozygotes had, at minimum, early evidence of disease-associated changes in their brain by age 65. The earlier onset and worse prognosis, Fortea and his colleagues argued, mean that this is a distinct form of AD for which the genotype is diagnostic. Affecting 2 percent of the world's population, they concluded, makes it "one of the most frequent Mendelian [single-gene] diseases."

Fortea and his co-authors, like the authors of the 2024 AA guidelines, emphasized that the point of reconceptualizing the disease is not to label healthy people with AD before a treatment becomes available. But that may be the real-world consequence of adopting these changes. Bioethicist Emily A. Largent, an associate professor and chief of the division of medical ethics at the University of Pennsylvania, has written about the social context in which a redefinition of AD will play out. "People are learning risk information in the absence of meaningful protections in key areas," Largent explains. "We really need to be thinking about what happens when the patient or research participant leaves the clinic, and now they have this information, and they're operating in the world."

Would you go to a surgeon or hire a lawyer who was found through testing to have positive biomarkers for Alzheimer's?

LARGENT AND HER COLLEAGUES conducted a study, published in 2020, about the impact of revealing AD-biomarker status to healthy adults aged 65 and older, and in many ways their findings echo the lessons of the REVEAL study. Participants with positive biomarkers experienced negative feelings but not "extreme distress."

They perceived the information as useful and made changes in their lives, including getting their finances in order, purchasing insurance, prioritizing "bucket list" activities and moving closer to family. But test results also changed the lens through which they saw their own experiences. Those who tested negative waved off minor lapses and "senior moments" as just what comes with normal aging, whereas those who tested positive saw them as evidence of disease. "We have some haunting quotes from people," Largent adds, "asking, basically, Is this how it starts? Is this how it begins?"

People who tested positive also worried about being viewed by others as dementia-adjacent. Largent found that concerns about stigma and discrimination were common and included fears of being treated differently by friends and family members. "They're like, 'I'm worried that my kids are going to take away the car keys or won't let me babysit my grandchildren,'" she says.

Participants also expressed concerns about potential discrimination by employers and insurance companies. Green has spoken many times about the extreme distress experienced not by *APOE* ε4 carriers but by insurance executives when they first heard about testing for the variant. "I got invited to all sorts of insurance meetings," he recalls. Companies worried that informed customers would buy long-term-care insurance only if they were at increased risk, shifting the actuarial landscape. Now ethicists worry that as testing becomes easier to access and more routine, insurance companies may turn the tables on their customers, refusing coverage to people who are biomarker-positive or *APOE* ε4 homozygotes.

Worries about employment discrimination are not unfounded. Under the Genetic Information Nondiscrimination Act (GINA), passed in 2008, U.S. employers are forbidden from discriminating against employees on the basis of genetic information. But redefining biomarkers and genotype as diagnostic may make employees more vulnerable. GINA's protections do not extend to what is called "manifested disease," which the U.S. government defines as a disease at a stage where it could reasonably be diagnosed by a health-care professional. What protections survive when one's genetic makeup is declared diagnostic?

People who test positive for AD biomarkers might find their employers disinclined to embrace a wait-and-see attitude, especially if they perceive liability in having an employee at high risk for cognitive impairment. Would you go to a surgeon or hire a lawyer who was biomarker-positive for AD? Would you consider that status something they should be required to disclose? The idea of AD as a continuum is intended to facilitate early intervention but could end up making people hesitant to seek care or participate in clinical trials that require they be tested for biomarkers or AD genes. "Ultimately," Largent says, "I think that we might really limit our ability to recruit people for research if we don't come up with adequate protections for people outside the research setting."

Both the 2024 AA guidelines and Fortea's paper emphasize that the answer is to discourage testing healthy people outside of research settings until better treatments are available. But testing is no longer entirely in the control of clinicians or professional organizations. *APOE* screening has been a direct-to-consumer option for more than a decade, and the first biomarker blood test available for purchase was announced in 2023.

Even if you intend to offer the test only to people who are symptomatic, where exactly do you draw that line? Dementia does not emerge fully formed like Venus from her shell. By all reasonable measures, my mother was cognitively intact that morning in Rome. Later, as her confusion advanced, she agreed when I urged her to see a doctor and then reneged, telling me tearfully that she was afraid to hear the diagnosis. Would the delay afforded by medication have been compensation enough for living the last decent year of her life under the cloud of a diagnosis? These are new questions for an aging population.

"It's an important step forward in medicine," Green notes, to redefine conditions according to their biology and not clinical manifestations that show up "late in the game." That, he adds, "is a strategy that has proved helpful in cystic fibrosis and sickle cell disease." But at the same time, Green concedes, the use of the word "diagnosis" might incorrectly suggest inevitability. For his *APOE* ε4 homozygote patients, he frames it as, "You're at increased risk for AD, but, you know, it's not for sure. And there's a good chance you'll die of something else. So let's not get too excited about this. Party on." REVEAL and other studies have shown that affected people who receive counseling can understand what is meant by "at risk." But as Largent's work demonstrates, educating the patients may not be sufficient if the society around them is unable to disentangle dementia's cognitive decline from the literal presence of its plaques and tangles.

Early identification of those at risk for dementia may be a mix of hazards and benefits for affected people and their families, but it is a clear boon for researchers and those marketing therapeutics. Presymptomatic diagnoses will boost sales of preventive measures and create a population of the worried well who will raise money and put pressure on government agencies to fund research, approve drugs and make sure they're covered. Identifying those most likely to develop dementia also could make clinical trials on the condition more efficient and less expensive.

For these reasons, there has been criticism of the makeup of the AA working group; a *New York Times* article reported that about a third of its members "are employed by companies developing drugs and diagnostics," and another third have disclosed "research grants or contracts, consulting fees, honorariums or other payments from industry sources." When asked by SCIENTIFIC AMERICAN, Jack said he has no conflict of interest and "honestly didn't see any kind of bias or commercial interest seeping in."

Let's assume that eventually there will be preventive measures that justify routine testing for early intervention. The fact is that a healthy adult diagnosed with AD today will face many uncertainties and few options, even if they contribute toward a potentially better future as a participant in ongoing research.

Our ability to define diseases by how they arise and not how they manifest is a powerful tool that permits us to better predict, diagnose and treat a whole range of conditions. "It's a pretty amazing moment," Largent acknowledges, "but the science is really outpacing policy right now. We are having all these changes in the midst of a system that needs to find new ethical, legal, social and clinical ways of helping patients and families." ■

FROM OUR ARCHIVES
The Urgent Need to Transform Dementia Care. Hilary Evans and John Bell; ScientificAmerican.com, April 15, 2024.
ScientificAmerican.com/archive

ASTRONOMY

The best view yet of a famous nearby blast reveals new secrets

BY CLARA MOSKOWITZ

ANATOMY OF A SUPERNOVA

CELESTIAL FIRECRACKER

Cassiopeia A is the aftermath of the closest known young supernova to Earth, a blast that occurred some 350 years ago. Recent data from the James Webb Space Telescope (JWST) combine in this image with earlier observations by the Hubble Space Telescope, the Chandra X-ray Observatory and the Spitzer Space Telescope to reveal a clearer picture of Cassiopeia A than ever before.

NASA/CXC/SAO (*x-ray*); NASA/ESA/ESA/STScI (*optical*); NASA/ESA/ESA/CSA/STScI/D. Milisavljevic et al., NASA/JPL/Caltech (*infrared*); NASA/CXC/SAO/J. Schmidt and K. Arcand (*image processing*)

AS SOON AS A STAR IS BORN, it starts fighting a battle with gravity. A burning star constantly releases enough energy to counteract gravity's inward pressure. But once its fuel runs out, gravity wins: the star implodes, and most of its mass becomes either a neutron star—an ultradense object about the size of a city—or a black hole. The rest explodes outward, flying into space like bullets.

Astronomers recently captured new images of the aftermath of this violence by training the James Webb Space Telescope (JWST) on the young supernova remnant called Cassiopeia A. The light from its explosion reached Earth about 350 years ago, around the time of Isaac Newton. "This particular object is very important because it's relatively nearby and it's young, so what you see is a frozen-in-time picture of how the star blew up," says Dartmouth College astronomer Robert A. Fesen.

Astronomers have studied this nearby spectacle for decades, but JWST got a closer look than any past observatory. "The Webb images are really amazing," says Fesen, who led the first team that studied Cassiopeia A with the Hubble Space Telescope. Hubble observes in primarily optical light—the wavelength range human eyes can see—whereas JWST captures longer-wavelength infrared light, and it does so with a larger mirror that captures images in higher resolution.

The recent photographs are helping scientists answer some of their most pressing questions about supernovae, such as which types of stars explode in which ways and how exactly those outbursts unfold. "There is a lot of complicated but beautiful physics in understanding how this explosion takes place," says Purdue University astronomer Danny Milisavljevic, who led the team behind the JWST images.

Stars start off burning hydrogen into helium inside their fusion furnaces. When the hydrogen is used up, they fuse helium to make carbon, then carbon to make neon, and so on, until they reach iron, which costs more energy to fuse than it releases. At this point the star begins to collapse under gravity, and its matter falls in until most of the protons and electrons inside its atoms have been smushed together to form neutrons. Eventually the neutrons can't collapse any further—they become a neutron star, where particles experience such extreme pressure that they trigger a repelling shock wave. (Only the most massive stars end their lives in supernovae. The sun, for instance, will fade to become a white dwarf.)

Astronomers still can't entirely account for the explosive power of a supernova. "It was thought that this rebounding shock that's produced when the neutron star forms could explode the star," Milisavljevic says. "But decades of simulations on the world's fastest computers showed that the rebounding shock isn't strong enough to overcome the massive layers on top that want to fall in." For now the core driver of supernova explosions remains a mystery. Researchers suspect the answer involves neutrinos, nearly massless particles that tend to pass through matter unimpeded. Perhaps at the intense temperatures and densities at the core of a star, some of the neutrinos' energy goes into reviving the shock. But more observations are needed to verify this idea.

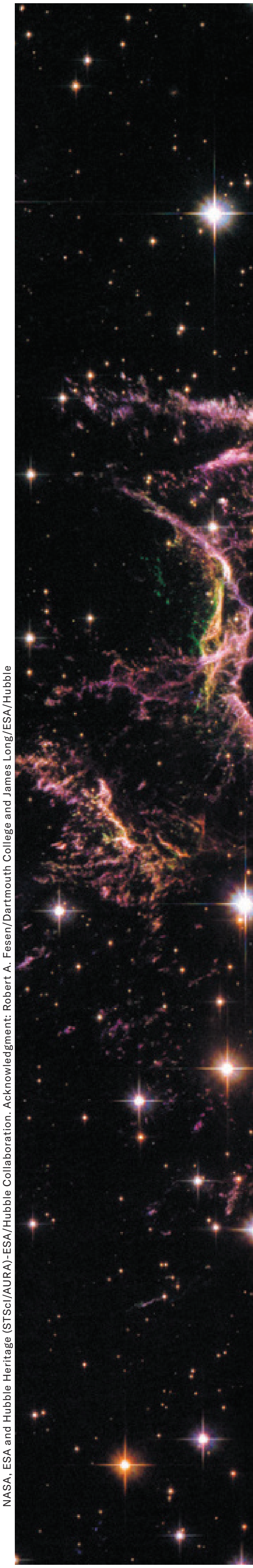
Among JWST's revelations about Cassiopeia A is a layer of gas that escaped its star during the blast. These JWST images show the gas before it interacted with material outside the star and before it was heated by a reflection of the shock wave the star expelled during its eruption. This pristine ejecta from the supernova displays a weblike structure that offers clues about the star before it exploded. "JWST gave us basically a map of the structure of that material," says Tea Temim, a Princeton University astronomer who collaborated on the JWST images. "This tells us what the distribution of the material was before it was ejected in the supernova. We haven't been able to see something like this before."

The investigation also exposed an unexpected feature of Cassiopeia A that scientists have named the "Green Monster." Astronomers think this layer of gas was expelled by the star *before* it exploded. "The Green Monster was an exciting surprise," Temim says. Scientists are interested in what happens when the supernova debris flies into the material in the Green Monster. "This is important," Temim says, "because when we observe extragalactic supernovae, their light is very much influenced by the surrounding material."

Deciphering the details of supernovae could even help us understand how Earth and its life came to be. Stars create the elements heavier than hydrogen and helium that life requires. Their end-of-life eruptions spew these elements into space, seeding galaxies with the raw materials to form new stars and planets. "As citizens of the universe, it's important we understand this fundamental process that makes our place in the universe possible," Milisavljevic says.

Astronomers will keep studying Cassiopeia A, although their success makes them eager to turn JWST's eyes toward some of the other roughly 400 identified supernova remnants in our galaxy. Getting a larger sample will help researchers connect differences in how remnants look and evolve to differences among the stars that produced them. ●

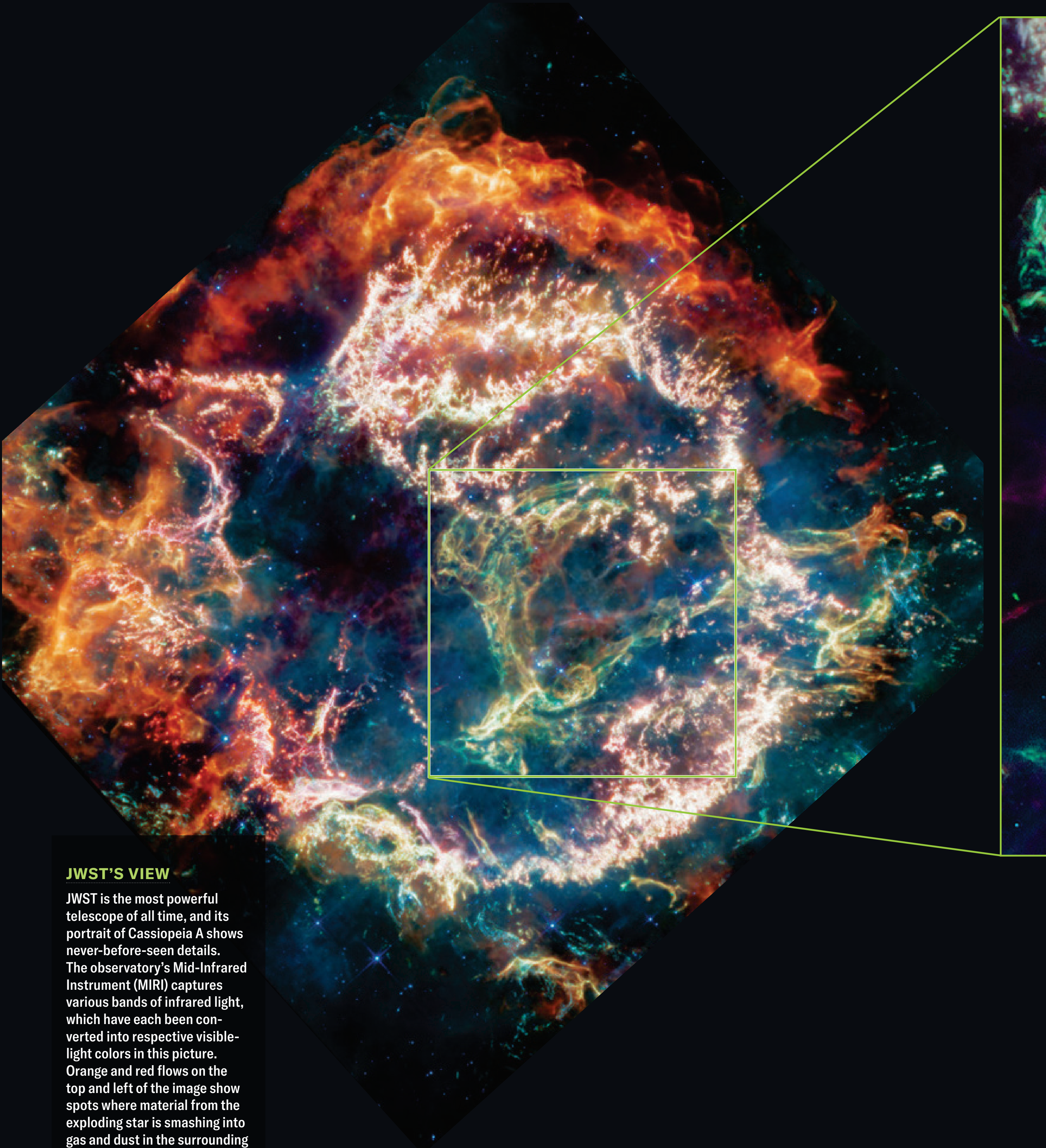
Clara Moskowitz is a senior editor at *Scientific American*, where she covers astronomy, space, physics and mathematics.



NASA, ESA and Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration. Acknowledgment: Robert A. Fesen/Dartmouth College and James Long/ESA/Hubble

HUBBLE'S BIG STEP

Before the JWST images, Hubble's observations of Cassiopeia A were revolutionary. In photographs taken in 2006, Hubble improved on the resolution of ground-based observations by a factor of 10. In the process, it was able to resolve clumps of material ejected during the supernova that were traveling shockingly fast, between 8,000 and 10,000 kilometers per second. "The explosion is ridiculously violent," Fesen says. "The outer layers of the star appear to fragment into clumps of gas, almost like the star shattered into thousands and thousands of pieces." Scientists hadn't realized that the blast would produce such clumps, Fesen says. "Nature had to show us that stars actually do that."



JWST'S VIEW

JWST is the most powerful telescope of all time, and its portrait of Cassiopeia A shows never-before-seen details. The observatory's Mid-Infrared Instrument (MIRI) captures various bands of infrared light, which have each been converted into respective visible-light colors in this picture. Orange and red flows on the top and left of the image show spots where material from the exploding star is smashing into gas and dust in the surrounding area. Inside this shell are bright pink strands released during the explosion. The dark red web toward the center left represents pristine structure from the blast that could hold clues about the star before it blew up.

FROM OUR ARCHIVES
Stellar Fireworks. Daniel Kasen; June 2016. ScientificAmerican.com/archive

NASA, ESA, CSA, Danny Milisavljevic/Purdue University, Tea Temim/Princeton University, Ilse De Looze/University of Ghent; Joseph DePasquale/STScI (*image processing*)

THE GREEN MONSTER

Zooming in on the JWST image reveals a surprise—a green bubble scientists are calling the "Green Monster" after a green wall at Fenway Park in Boston. This blob is made of gas layers the star cast off before it burst apart. "It looks weird and has this bizarre distribution of rings and filaments," Milisavljevic says. "Encoded in this puzzle is information about how the star was releasing mass before the explosion."

Holes apparent in the Green Monster seem to provide evidence of the clumps of ejecta Fesen and his team observed with Hubble. "The images from JWST show little holes, almost like bullet holes, that are almost perfectly round," he says. Scientists think the fast-moving clumps of supernova material are punching through the surrounding sheet of gas like shrapnel to create the holes. The size of the holes betrays the clumps' gigantic size—roughly 500 astronomical units (the distance between Earth and the sun). "As these clumps have been sailing through space, they've expanded to become bigger than the solar system," Fesen says.

NASA, ESA, CSA, STScI, Danny Milisavljevic (Purdue University), Ilse De Looze (UGent), Tea Temim (Princeton University)

CRYSTAL CLEAR

Another JWST instrument, the Near-Infrared Camera (NIRCam), showcases Cassiopeia A in shorter-wavelength light than MIRI. "The benefit of NIRCam is resolution," Milisavljevic says. "When you zoom in like this, it's astounding. I'm going to spend the rest of my career trying to understand the supernova at these scales." He hopes to use these data to understand how the shock wave of the explosion has shaped the gas it encountered, as well as how dense the supernova material can get, to garner clues about how the cataclysm unfolded.

NASA/ESA JWST, Danny Milisavljevic/Purdue University, Tea Temim/Princeton University, Ilse De Looze/University of Ghent and HST, R. Fesen/Dartmouth College; J. Schmidt (*image processing*)

Renew Support for Renewable Energy

Renewable energy is crucial to the U.S. economy and the environment **BY THE EDITORS**

Wind turbines create renewable energy and are part of the fastest-growing sector of electricity production in the U.S. Seen here is a wind farm in northern California's Altamont Pass.

INCOMING PRESIDENT Donald Trump and his administration have called warnings about climate change "alarmist," and they have pledged to further expand oil and natural gas production. But there are important reasons for the U.S. to expand its use of clean energy technologies as well. Renewable energy not only cuts carbon emissions; it is an economic juggernaut.

Renewable energy is growing faster than any other electricity source in the U.S., according to the U.S. Energy Information Administration. Globally, the market for these technologies is projected to rise from $700 billion in 2023 to more than $2 trillion by 2035.

China dominates the worldwide markets for solar panels, electric vehicles, and batteries able to store energy when the sun or wind is down. If the U.S. does not support domestic renewable-energy industries, China's dominance will only grow, with the European Union and India poised to also rise. If the Trump administration stops federal support for renewables or, worse, discourages them, the nation will both continue to degrade its environment and miss a profound economic opportunity. "This is ceding the future," says Steven Cohen, director of Columbia University's master's program in sustainability management.

More renewables also means greater U.S. energy independence, and right now it means more support for domestic industries. According to an August 2024 report by the Rhodium Group and partners, the five states receiving the most clean energy and clean technology dollars from the Inflation Reduction Act, relative to the size of their economy, are all red or "swing" states: Nevada, Wyoming, Arizona, Tennessee and Montana. There is plenty more cash from the Inflation Reduction Act to hand out—unless the Trump administration dismantles the legislation.

That would be a mistake. A rise in renewable energy does not mean a fall in oil or natural gas. U.S. production is growing there, too, and overall power demand is increasing. We're not proposing a future free of fossil fuels. Major energy transitions take time. But as numerous studies have shown, more fossil-fuel consumption makes climate change, air and water pollution, and public health worse. Ultimately renewable energy costs less, and the cheaper technology always wins. Some U.S. states have gotten this message: Texas, the oil center of the country, now produces more wind power than any other state. The market for clean technologies is "increasingly catching up with the markets for fossil fuels," Fatih Birol, executive director of the International Energy Agency, noted in an October 2024 release of the agency's latest study.

A common refrain from critics is that U.S. renewable-energy industries depend on subsidies. Truth is, that's how canals, roads, trains, steel, aluminum, corn, soybeans and space rockets developed, too. And even though the U.S. oil and gas industries are more than a century old, they still get huge subsidies as well. China subsidizes its renewable-technology industries—and for the rest of the world, that's positive. Inexpensive Chinese solar panels, electric cars and wind turbines help to accelerate the energy transition worldwide. Energy transitions are costly, notes Jeffrey Frankel, professor of capital formation and growth at Harvard University and a research associate at the U.S. National Bureau of Economic Research. So, he asks, why not let Chinese taxpayers foot a subsidy bill that helps to spread renewable energy everywhere?

Billy Hustace/Getty Images

Capitol Hill's view of the renewable-energy industry may be influenced by the strong fossil-fuel industry lobby. But the big users of renewable energy have strong influence, too. More than 70 percent of the U.S. gross domestic product now comes from the service sector, according to the U.S. Bureau of Economic Analysis, and it is gaining in political power. Meta is the largest buyer of solar panels in the country. The service sector consumes gobs of energy; witness the meteoric rise in energy demand from artificial-intelligence data centers. These companies want the cheapest power prices, and renewables offer them. "Money tends to dominate over ideology," Cohen says.

Most people recognize that climate change is real and a result of our own actions, notably, burning fossil fuels, which they increasingly see as harmful. According to a large 2023 survey by the Pew Research Center, "59 percent [of Americans] think that air and water quality would get better if the U.S. greatly reduced fossil-fuel energy production and increased production from renewable sources." The survey also found that "67 percent of Americans say the U.S. should prioritize developing alternative energy sources, such as wind, solar and hydrogen technology, while 32 percent say the priority should be expanding the exploration and production of oil, coal and natural gas."

A cultural shift is underway, in part because many more people in the U.S. are experiencing extreme weather: most recently, unprecedented flooding in North Carolina from Hurricane Helene and record-breaking drought killing crops across many states. Homeowners in some coastal states cannot get flood insurance. These experiences put millions of Americans at great risk of death, injury or financial ruin. People can see that the scientific predictions have been correct all along. They are increasingly worried about their health and their children's well-being. They are feeling the human impact.

Supporting renewable energy is not asking anyone to do without—we won't have to give up our trucks or air conditioners. It provides an opportunity to reduce the threats we all face and to lead in a rapidly expanding, thriving economy. ⬢

Overcoming Solastalgia

Environmental damage can cause a profound sense of loss, but it can also inspire

BY QUEEN ESSANG

AS I SIT in my backyard in Abuja, Nigeria, looking out at the open landscape around me, I can't help but feel a deep sense of loss. The rolling hills that were once richly carpeted with wild ferns, daisies, lupines and goldenrods are now dotted with invasive species that have choked out the native flora. The river that was once crystal clear, reflecting the azure sky and teeming with darting fish as dragonflies glided by, is now muddied by sediments and pollutants from nearby construction and agriculture.

This feeling of loss and dislocation, a combination of nostalgia for what once was and profound sadness for what has been irretrievably altered, has a name: solastalgia. Coined by philosopher Glenn Albrecht, it is the emotional distress caused by environmental change, particularly when it affects the place we call home. Essentially it is the feeling of being homesick while at home.

Despite the pain of this feeling, there is hope. Solastalgia has inspired me. It serves as a strong motivator to push for the protection and rejuvenation of our environments. It reminds us of the intrinsic value of nature and the importance of stewardship. When we acknowledge our grief and channel it into positive action, we empower ourselves to fight for the landscapes we love and to safeguard biodiversity, transforming our sorrow into tangible steps for change. Our bonds with nature are resilient and worth nurturing for future generations.

Growing up, I spent countless hours in the woods behind my childhood home surrounded by majestic oaks with their sprawling canopies, towering pines reaching for the heavens, and graceful willows swaying gently by the river's edge. I would often find myself in the embrace of the ancient pines, their earthly scent grounding me as I wandered underneath their branches. The woods were my sanctuary. Each tree had a story, a memory attached to it. I remember the laughter of friends echoing throughout the canopy as we played hide-and-seek, the sun filtering through the foliage, casting dappled shadows on the forest floor, and the quiet moments spent sitting up against a tree trunk, feeling at one with nature.

When I returned home after five years in college, I was struck by how much the ecosystem had changed. As climate change accelerates and development encroaches on familiar spaces, I find myself grappling with an unsettling reality. The vibrant tapestry of my childhood is unraveling. In its place lies a landscape marked by change—change that feels invasive and alien.

Today, in my backyard, I find myself thinking about the day years ago when I encountered a friendly female waterbuck while wandering through the lush Stubbs Creek reserve. The forest was alive with playful squirrels, and the occasional fox darted through the underbrush. Chirping robins and warblers and buzzing insects created a symphony that sounded like home. Now I realize many of those trees have been felled, replaced by sterile housing developments devoid of the forest's life and character.

Nestled within this vibrant landscape was Ibeno Lake. I had taken pride in its clear water, where families of ducks and geese often swam grace-

Queen Essang lives in the Federal Capital Territory (FCT), Abuja, Nigeria, and works as a freelance writer focusing on environmental issues and their psychological impact. She has a degree in botany and ecological studies from the University of Uyo in Akwa Ibom State, Nigeria, and was involved in the strategic implementation of climate change action and mitigation measures in the FCT administration's department of forestry.

Crude oil pollutes the shoreline of an estuary in B-Dere, Ogoni, Nigeria. Residents are trying to sue Royal Dutch Shell for the environmental damage.

fully by. The lake was joy: a place for summer swims, lazy afternoons spent floating on rafts, evenings filled with the laughter of friends gathered around bonfires. It was here that I learned the rhythm of nature. Now I watch in dismay as algae blooms choke the water, turning it a murky green.

The emotional turmoil is not mine alone; it resonates with many people who are witnessing similar transformations in their environments. The deep sense of solastalgia manifests as a grief that is often overlooked—a sorrow not for a person but for a place. It is a longing for a connection that feels increasingly out of reach as the landscapes we once knew and loved are irrevocably altered.

Every time I see a familiar landmark disappear or a beloved habitat shrink, I can't help but reflect on how a once vivid collection of biodiversity is transforming into a homogenized landscape. This transformation induces a precarious tipping of nature's equilibrium. Climate change is a fundamental cause, but pollution from nearby industrial complexes has contributed significantly to the degradation of the natural environment. Deforestation spurred by the relentless pursuit of urban development continues to erode extensive forestland, and unsustainable extraction has stripped the land of its natural resources, leaving scars that are slow to heal.

I cannot stand idly by. I began to educate myself about conservation efforts shortly after I returned home, driven by the changes I witnessed in my environment. I have joined local conservation groups, participating in tree-planting initiatives to restore native species and combat the invasion of nonnative flora. I have also engaged in cleanup efforts at Ibeno Lake, rallying friends and family to help remove litter and debris from the shorelines so we can restore its natural beauty. Education is vital, too; I strive to raise awareness in my community about the importance of preserving our natural spaces.

In my conversations with family and friends, I find that solastalgia is a common experience. We often reminisce about the landscapes of our youth, remembering the places that influenced our lives. These discussions take on a somber tone as we realize our memories are becoming associated more with what we are losing than with what is left. The world is changing, and as a result, so are we.

As I reflect on my journey with solastalgia, I realize it is not merely a feeling of loss but also a call to reconnect. It urges us to find new ways to engage with our surroundings, to create memories in the face of change and to honor the beauty that still exists, despite the challenges. Although the landscape may shift, our appreciation for it can remain steadfast, reminding us that our bond with nature is resilient and worth nurturing for future generations.

In an era when environmental challenges loom large, solastalgia serves as a poignant reminder of what is at stake. It is an invitation to cherish our homes, to advocate for their protection and to cultivate a deep-rooted sense of responsibility for the world we inhabit. As we confront the realities of a changing climate, may we find solace not only in our memories but also in our collective capacity to foster a thriving future for both people and the planet, in a harmonious balance that nurtures the vibrant tapestry of life. ⬢

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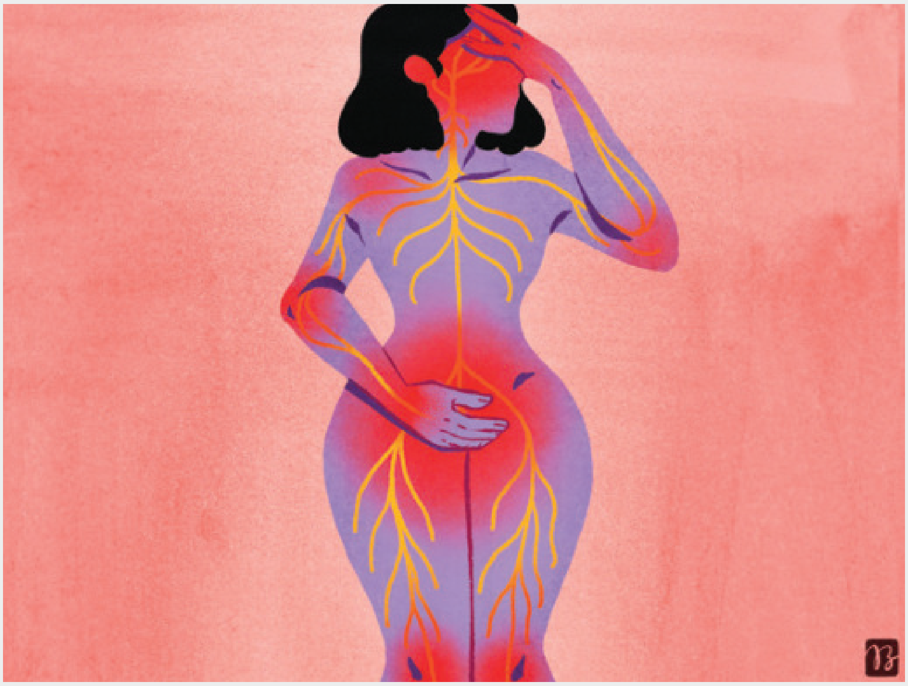

Not Just a Pelvic Problem

Endometriosis is linked to migraines, asthma, and more BY LYDIA DENWORTH

THE PAIN from endometriosis, which affects an estimated one in 10 Americans born female, can be terrible. Some people are unable to work or go to school. Yet many physicians don't recognize the symptoms. On average, it takes sufferers seven to nine years to get a diagnosis.

That startling statistic, along with the general lack of familiarity with endometriosis, is a powerful example of the gap in knowledge about women's and men's health. There has been limited funding and investigation into what causes endometriosis or who is at highest risk. That is finally changing, in part because the understanding of endometriosis is changing. It is not purely a gynecological condition. "In the past three to five years there's been a complete reframing of this disorder as a neuroinflammatory whole-body condition," says reproductive biologist Philippa Saunders of the University of Edinburgh. "It isn't just about a little bit of tissue stuck in the wrong place. Your whole body has reacted."

Endometriosis, which involves tissue from the uterus, begins with a process known as retrograde menstruation, in which menstrual blood flows back up the fallopian tubes and into the pelvis. The blood carries bits of endometrial tissue, which lines the uterus. Sometimes, instead of being cleaned up by the immune system, this tissue adheres to the ovaries or pelvic lining, then grows and creates its own blood supply. The lesions can cause infertility as well as debilitating pain. "We're not talking a little bit of pain here," Saunders says. "[People] can't function." And unlike menstrual cramping that occurs during a period, pain from endometriosis can flare at any time.

The medical profession's habit of restricting health issues to narrow silos—traditionally, only gynecologists saw endometriosis patients—hasn't helped. "We chop up human health into specialties and systems, but we know now that [those systems are] much more interconnected than we had presumed," says Stacey Missmer, a reproductive biologist at Michigan State University. Endometriosis creates symptoms and consequences that affect many other parts of the body, she points out.

For example, adolescents and young women with endometriosis are five times more likely to be diagnosed with irritable bowel syndrome than women with no endometriosis. Cardiovascular events are rare in all women younger than 60, but in those with endometriosis, the relative risk of high blood pressure, stroke, angina or heart attack increases by 20 to 80 percent, depending on the study and condition. Patients are at twice the risk of rheumatoid arthritis, and asthma, lupus and osteoarthritis have higher prevalence among people with endometriosis. These people are also more likely to suffer from overlapping conditions such as migraines, low back pain and fibromyalgia, a chronic pain condition.

Scientists cannot yet say for sure why these conditions are so often seen together. "We think one of the key pathways is chronic inflammation," Missmer says. It could be, for instance, that affected people have inflammatory responses to certain triggers that some diseases share.

Researchers do know that about half the risk of endometriosis results from genetic factors. Although early studies failed to find a common high-risk gene for the condition—one akin to the *BRCA* gene for breast cancer—more recent large-scale work has implicated genetic variations across the genome. A 2023 study in *Nature Genetics* of about 60,000 people with endometriosis and over 700,000 without the condition found more than 40 places in the genome that harbor changes associated with a higher risk of the disease. "That really led to a jump in our understanding," says genetic epidemiologist Krina Zondervan of the University of Oxford.

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

Illustration by Jay Bendt

That jump, in the same study, allowed researchers to highlight shared biology in some of the diseases that often co-occur with endometriosis. For instance, they found a link in the genetics underlying endometriosis and other types of pain, such as migraines. Such pain conditions trigger a biological process called central sensitization, which occurs when chronic pain changes the way the central nervous system reacts to pain stimuli, and many of the genes involved are associated with pain perception or maintenance. They also found links to inflammatory conditions such as asthma.

What may help with diagnosis and treatment is the recent recognition that endometriosis is not a single disease. It's a condition with three subtypes. Ovarian endometriosis, which results in lesions on the ovaries, is the most heritable. Deep endometriosis infiltrates farther into the pelvis and produces very hard nodules. In peritoneal or superficial endometriosis, smaller lesions scatter more diffusely along the pelvic lining. As in breast cancer, the subtypes most likely have different risk factors.

Until recently, the only way to diagnose endometriosis was laparoscopic surgery. But now less invasive methods are being used. Ultrasound imaging can spot ovarian endometriosis, for instance, and an MRI scan can reveal lesions of the deep form. Unfortunately, imaging doesn't yet work well for peritoneal endometriosis, the most common type. Also, patients need to be referred for such imaging, and not everyone is because of misdiagnosis and inequities in health-care access.

For treatment, surgical removal of lesions works for some but not all patients. Identifying the accompanying conditions may determine who won't be helped. Those suffering from widespread pain beyond the pelvis may not benefit from surgery. "There's not something to cut out," Missmer says. Clinical trials are underway in the U.K. to study outcomes with and without surgery.

Right now anyone with a diagnosis of endometriosis or with worrying symptoms should discuss it not just with a gynecologist but with their primary doctor, too. This is not a one-body-part problem. ●

MENDELEEV'S NIGHTMARE

I went to my rest a sober man, content with the stable progression of elements I found
to be more reliable than any prayer. Sleep came easily. I went deep, then deeper,
until in a single instant I fell straight through the lattice of all-that-is.

Diced, I arrive into this hell scape, my sobriety sieved, irretrievable.
A man dressed in black dips the tip of a thin moustache into pot after pot of color.
With a theatrical swoop, he renders all-that-was-rectilinear down to violent,
vertiginous curves, which drip like fluorescent tallow

tock tock tock
off the edge of the known world.

He turns to me and seals my throat with the same, whispers *only memory persists.*
Then, lifting his shoe hat, winks horribly, and recedes at implausible speed toward a
doorway newly there. I stumble after him, desperate to find what order might remain.

We stand on the threshold. I could wish my ears stopped with wax. A brass band
decibels down the street, while ranks of percussive skeletons dance past bearing aloft
faux-gold balloons. They are on their way to the ceremony where what-is-lost (as
light and unwilling as any child bride) must wed what-remains-forever. My rage
swells. I will find a way to annul this marriage made in hell. Twisting free, I run
backwards and slip into an alley where it is dim and the carnival din quietens.

tap tap tap tap

Have I arrived tongueless, then, in the land of the blind? Slowly my eyes and ears
adjust. Up ahead I see street gangs gathered to scry the uncertain future. I draw closer.
A young girl crouches, dressed in rags. She stares so fixedly at what is before her that
she does not see me. I look over her shoulder, read the words that appear and fade on
her handheld screen: *How to recover silver from X-rays.*

I cough and spit out fractured wax. It is critical I speak.

The ghosts are in the machine.

Liana Christensen is an Australian poet whose published works include *Deadly Beautiful, Wild Familiars* and *Unnatural History.* This poem was inspired by the European Chemical Society's revised periodic table, depicting element scarcity, which struck Christensen as "Dali-esque."

Illustration by Olga Aleksandrova

Emotions Are Not Gendered

Expecting children to express or suppress emotions based on their gender harms them

BY PRAGYA AGARWAL

A COUPLE OF YEARS AGO I was at the ophthalmologist with my six-year-old daughter. The optician asked me more than once, "Why has she been frowning all the time? Why is she so serious?"

I cannot know how much my child's being a girl shaped the optician's thoughts about her emotional state. But I know from my research on the gendering of emotions that people start expecting women and girls to show nurturing and positive expressions early. A different group of researchers analyzed more than 16,000 yearbook photographs of students from kindergarten to college, as well as school faculty and staff. The children showed no significant difference in smiling until age eight or nine, but then the gap started to widen, with girls smiling much more than boys. The difference between girls and boys peaked by the time the students were 14 years old, with girls smiling more frequently and more broadly than boys, and this contrast remained consistent over adulthood.

Pragya Agarwal is a behavioral and data scientist, a freelance journalist, and author of the book *Sway: Unravelling Unconscious Bias* (Bloomsbury, 2020).

We may see such results because as children grow older, they become more aware of societal expectations related to gender roles. These expectations could come from peer groups or be imposed on them by parents, teachers or, in the case of the yearbook photos, photographers, both implicitly and explicitly. People may also internalize gender roles portrayed in film and media, where smiling is perceived as more feminine (smiling women are considered more pleasant and friendly) and seriousness is seen as a characteristic of masculinity.

In a different study in which teachers reported their students' emotional expressions, girls were described as having more "peaceful," "calm" and "neutral" expressions (all positive but passive emotions involving little agency), whereas boys showed more "surprise," "curiosity," "anger" and "frustration" (more agentic, or proactive, emotions). It is a widely held misconception that girls are better than boys at regulating their emotions: no neuroscience studies have shown that self-regulatory mechanisms are more developed or active in girls than they are in boys.

Society expects brown women to be more acquiescent and perceives Black women who aren't acquiescent as angry. As a mixed-race girl, my child is likely to encounter some of these stereotypes. A study of American storybooks showed that Hispanic and Latino characters display happiness proportionally more than other characters, whereas white American characters have the space to show displeasure, aligning with the individualistic values of many Western cultures. Children may receive specific messages about emotions while reading storybooks—not only gendered but also culture-specific.

These emotional stereotypes present a double bind for parents hoping to help their children develop emotional intelligence and autonomy. Very early on, children learn to modulate their emotions in line with societal norms they pick up from their peers and caregivers. Regularly suppressing our emotions can massively affect our mental and physical

Illustration by Malte Mueller/Getty Images health. Emotional expectations and the offhand comments that children internalize over time harm all kids, irrespective of gender. These expectations can have long-standing negative effects on their sense of self, too. If, however, children do not conform to the behaviors and norms of their membership groups, they may face bullying.

Teaching our children to regulate their emotions is not wrong. Emotional socialization is an important part of parenting to build children's emotional competence and to align them with the values of a particular community. But it is wrong to expect different things from our children based on their gender and race and to minimize or invalidate their emotions based on what we perceive as the correct emotional response. We talk with our children about bodily autonomy; we should also talk about emotional autonomy and how they can better understand and have agency over their own feelings.

Recently I have been reflecting on my relationship with emotions and how I might have endorsed certain expectations through words and actions. According to psychologist John M. Gottman's meta-emotion framework, parents' attitude toward emotions and the way they accept or reject certain ones in themselves affect which emotions they validate in their children.

Many people grew up with very specific emotional rules and model them in their own parenting, consciously or unconsciously. Parents are more likely to validate their child's emotions if they consider those emotions acceptable in general, and they are unlikely to if they believe the cost of expressing the emotion is too high. This cost could be the burden of societal judgment, penalization or ostracization, or it may be an emotional cost the parent pays by having to regulate their own emotions in response.

One study found that mothers were more likely to use emotional language when speaking with four-year-old daughters than with sons that age. Before the start of this experiment, the researchers had observed no difference in emotional understanding and expression between girls and boys, but this changed over the course of the study.

> So many problems emerge from adults' failure to accept the discomfort that comes with children's emotional expression and the way that leads them to set rules for "good girls" and "good boys."

Through the gendered use of language around emotion, children receive a message that certain emotions are more acceptable for girls than for boys and that women talk more about their feelings. Research also shows that parents might react—often unconsciously—in a way that encourages emotional expression in girls but discourages emotional expression in boys. These cues might include ignoring, dismissing or invalidating certain emotions in children: anger in girls and sadness in boys.

So many problems emerge from adults' failure to accept the discomfort that comes with children's emotional expression and the way that leads them to set rules for "good girls" and "good boys."

Anyone might be fearful of people judging them in public and seeing them as bad parents who cannot control or discipline their children. We label emotions as "good" or "bad": happiness is good, anger and sadness are bad. And we may discourage or shy away from any "bad" emotions our children express that might make us feel like we are not being good parents. Even our implicit gestures, facial reactions and tone of voice can give children signals from a young age as to which emotions are acceptable and which we should hide away or suppress.

Marc Brackett, director of the Yale Center for Emotional Intelligence, proposes that parents have to find their "best selves" before they can help their children with extreme emotions. From my standpoint, a better approach would be to stop labeling some emotions as "extreme," avoid setting such fixed bounds around emotional expression and not expect children to all conform to the same template.

If we reflected on the messages we internalized while growing up, we could allow ourselves and our children to sit with the discomfort of such "negative" emotions. Over the years, I have realized that it is not my responsibility as a parent to always protect my children from sadness or anger. Children ought to know that such emotions are part of our everyday life—that it is okay to feel sad, frustrated and angry. It is what we do with these emotions that matters.

Teaching children to understand how they are feeling and learn strategies to tackle their emotions is a way of encouraging their emotional autonomy. It is also important for children to know the correct vocabulary so they can name their emotions for themselves and others.

After our visit to the ophthalmologist, my child wondered, "Mummy, should I have been smiling?" I reminded her that she did not have to fake a smile. But even as I have taught her that she doesn't have to modulate or suppress her emotions for anyone else, I have wondered anxiously how much others will judge her for not conforming and what the cost of that will be. I am not suggesting that we each take individual responsibility for resolving the emotional biases in society that perpetuate and enable gender and racial inequities. But we can all reflect on our internal emotional framework and challenge emotional norms, acknowledging that we might be enforcing some of these arbitrary rules, without even realizing it, through our words and our actions. ●

For the most current, rigorous evidence to help you make the best decisions, go to **www.ScientificAmerican.com/report/the-science-of-parenting**

Tostphoto/Getty Images

A Gargantuan Prime Number

Discovery of a 41,024,320-digit prime number highlights the price of mathematical gold

BY JACK MURTAGH

THOUSANDS OF COMPUTERS across the world are currently scouring the number line in a scavenger hunt for rare mathematical gems. Enthusiasts looking for larger and larger prime numbers, which are divisible only by 1 and themselves, muster vast amounts of computing power and algorithmic ingenuity in hopes of etching their name into the scrolls of math history.

Last fall a new entry came from Luke Durant, a researcher in San Jose, Calif. Durant's discovery unseated the former record holder for the largest prime, which had gone uncontested for nearly six years, an unprecedentedly long reign in the modern search for such numbers. The gap makes sense: the bigger primes are, the further apart they end up, making each new find harder than the last.

The new prime contains a mind-boggling 41,024,320 digits. To put that in perspective, the estimated number of atoms in the observable universe has around 80 digits. Each additional digit increases a number by 10 times, so the size of the new prime lives far beyond human intelligibility. Primes play a major role in pure math, where they're main characters in a field called number theory, and in practice, where, for example, they underlie widely used encryption algorithms. A prime with 41 million digits won't immediately join the ranks of useful numbers, but for now it adds a feather in the cap of a community that longs to apprehend the colossal.

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Durant's success stems in part from new, clever software from the Great Internet Mersenne Prime Search and in part from heavy-duty hardware and computational muscle that he personally mobilized for the pursuit. By assembling a "cloud supercomputer" spanning 17 countries, he ended a long tradition of personal computers discovering primes.

Prime numbers are often called the building blocks of math because every whole number greater than 1 is either a prime or the product of a unique collection of primes. For example, 15 is the product of the primes 5 and 3, whereas 13 cannot be subdivided in this way, because 13 is prime. The study of these numbers dates back at least to the ancient Greeks. In 300 B.C.E. Euclid proved in his textbook *Elements* that infinitely many primes exist, and mathematicians, both professional and amateur, have relished the hunt for them ever since.

The first string of primes—2, 3, 5, 7, 11, and so on—is easy to find, but the task gets considerably more challenging as the numbers get larger. For millennia, people found primes by hand—until 1951, when computers took over the search. But even silicon bounty hunters struggle to spot primes in the far reaches of the number line because testing the primality of an enormous number is nontrivial. To cope, researchers deploy every little optimization trick they can to speed up their tests or narrow their hunting ground, thereby boosting their chances of finding a new prime.

Consider the number 99,400,891. How would you determine whether it's prime? You could simply divide it by each smaller number one at a time to look for any divisors (in addition to 1 and itself). But that's nearly 100 million cases to check for a relatively puny eight-digit number. You would save significant work by realizing that you don't need to check every number up to the target, just the *prime* numbers. Why? Because you need to find only one divisor (one number that cleanly divides 99,400,891 with no remainder).

We know that any nonprime divisor could be further broken down into its prime factors—if your target is divisible by 15, then it's also divisible by the primes 5 and 3, so you need to check only the latter to determine primality. More savings would come from the insight that you don't need to check every smaller prime, either—only those up to the square root of 99,400,891 (the number that, when multiplied by itself, gives you this eight-digit result) have to be tested. If none of those smaller primes divide it cleanly, then you can stop looking because the product of any two numbers larger than the square root of 99,400,891 will exceed it. These efficiency tricks slash our search drastically from around 100 million numbers to only 1,228 (the number of primes less than the square root of 99,400,891). For those curious, 99,400,891 = 9,967 × 9,973, so it's not prime.

Those shortcuts did wonders for an eight-digit number, but how did Durant reach 41,024,320 digits? To graduate the search from the merely massive to the truly gargantuan, he and many other seekers focus on particular types of prime numbers. Mersenne primes, named for Marin Mersenne, the French theologian who studied them in the 17th century, take a special form. You get them by multiplying 2 by itself some number of times and then subtracting 1, as described by the equation $2^n - 1$. Mersenne noticed that when you plug in different values for *n,* you sometimes get a prime number. Specifically, $2^n - 1$ can yield a prime only when *n* is prime, and even then it's not guaranteed.

What makes Mersenne primes special from a prime hunter's perspective is that we know a fast method for checking whether numbers of the form $2^n - 1$ are prime. That test is called the Lucas-Lehmer primality test (named for French mathematician Édouard Lucas, who first discovered it, and American mathematician Derrick Henry Lehmer, who proved and refined it). It is much faster than any of the known general methods for numbers without that special form.

The Lucas-Lehmer test fuels the Great Internet Mersenne Prime Search project, which launched in 1996 and enables any volunteer to download a free code that they can run on their computer to search for Mersenne primes. The crowdsourced approach and the focus on Mersenne

Even silicon bounty hunters wielding powerful computers struggle to spot primes in the far reaches of the number line.

primes have proved successful. The seven largest known primes are all Mersenne primes and were all found by participants in the project. Note that smaller *unknown* primes certainly exist, but because we don't know efficient methods for checking them, they'll remain in the shadows for now.

All told, project volunteers have found 18 new Mersenne primes, 17 of which owe their discovery to the personal computers of hobbyists. Durant, a 36-year-old former Nvidia engineer, broke that streak. Nvidia, which recently briefly overtook Apple as the world's most valuable company, designs specialty computer chips called graphics-processing units (GPUs). As the name suggests, GPUs were originally invented to accelerate the rendering of graphics, but they also excel at other tasks involving highly parallelized computation, in which many processors run simultaneously to solve problems. Those problems include training neural networks such as GPT-4, mining cryptocurrency and, as it turns out, foraging for primes. Durant assembled a global supercomputer by buying processing time from various cloud GPU providers. At its peak, his project churned through about 12 times as many numbers as every other computer involved in the Mersenne prime search combined.

In addition to the heavy-duty hardware, the software used for the Mersenne prime search also got a notable upgrade since the last discovery. The superfast Lucas-Lehmer test for certifying Mersenne primes was replaced in the programming with a super-duper-fast probable prime test. Given a number to check, the latter test either confirms that it's not prime or says that it's *probably* prime. Probable primes have a very small chance of turning out to be nonprime. Only once a computer finds a probable prime do volunteers in the Mersenne prime search run the full-fledged Lucas-Lehmer test to remove any doubt.

Durant's new prime passed the probable-prime test on October 11. Then, on October 19, a year after he started searching, independent tests by the Mersenne prime search confirmed that he had indeed found a needle in a haystack: $2^{136,279,841} - 1$ is the largest known prime number.

It exceeds the previous record holder by more than 16 million digits. If that didn't earn Durant enough glory, he has also unearthed the largest known "perfect number." A perfect number equals the sum of its divisors (excluding itself); 6 is perfect because it's divisible by 1, 2 and 3 and equals the sum of 1 + 2 + 3. The second perfect number is 28. Eighteenth-century Swiss mathematician Leonhard Euler proved that every even perfect number can be generated from a Mersenne prime, so finding one promises a two-for-one deal on math discoveries.

The well could dry up anytime, though. We don't know whether an infinite number of Mersenne primes (and therefore even perfect numbers) exist. Curiously, we don't know whether any odd perfect numbers exist, a question that some call the oldest unsolved math problem.

When asked how much money his project cost in an interview with Numberphile on YouTube, Durant said, "I believe it's under $2 million." That's a hefty investment compared with the prime-search project's prize of $3,000, which he plans to donate to the high school he attended, the Alabama School of Mathematics and Science. At this point, you might wonder why so many people spend their time and money trolling for primes that don't have obvious real-world applications. In part, their efforts celebrate human curiosity and serve as a benchmark for our progress in mathematical computation. But I think the founder of the Great Internet Mersenne Prime Search, George Woltman, when asked this question in a Numberphile video, said it best: "It's fun." ⬣

Marie Curie's Hidden Network

How she recruited a generation of women scientists BY CLARA MOSKOWITZ

MARIE CURIE, born more than 150 years ago, is still the only woman scientist many people can name. The double Nobel Prize winner is most famous for her discovery of radioactivity and of the radioactive elements radium and polonium. She is less well known for encouraging a generation of women who worked in her laboratory and went on in research because of the path she paved. Although few women in science have reached Curie's level of fame and name recognition, they continue to make gains because of her life and example.

In her book *The Elements of Marie Curie: How the Glow of Radium Lit a Path for Women in Science* (Atlantic Monthly Press, 2024), author (and *Scientific American* poetry editor) Dava Sobel chronicles Curie's life and work and sketches biographies of many of the women who worked with her. Sobel found that few people are familiar with the network of researchers Curie nurtured, as well as many other aspects of the renowned chemist's history. "Everybody knows her name, but hardly anybody knows anything about her," she says. Curie died of illness related to radiation exposure in 1934.

SCIENTIFIC AMERICAN spoke with Sobel about Marie Curie's contributions to science, history and gender equality.

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An edited transcript of the interview follows.

How did you learn about the female scientists Curie worked with?

In 2020 I was asked to review a book called *Women in Their Element,* a collection of essays about female chemists. The only two names I recognized to begin with were Marie Curie and her daughter Irène Joliot-Curie. But then as I read, I was really struck by the number of women who had spent some time with her either studying under her or working in her laboratory. By the fifth or sixth one, it really started to look like a network. And through the Curie Museum in Paris, I discovered there were at least 45 women who passed through her lab. She was the first woman ever to teach at the Sorbonne. And then that made her a magnet for these other women. Also, she was already world-famous because she had won the Nobel Prize in 1903 and in 1911, and that spread her name everywhere. So I thought, well, this is something about Madame Curie that most people don't know, and that's how I got started.

How did Curie end up making the huge discoveries she made?

She had extraordinary drive to get herself out of Warsaw to Paris, to be able to get an advanced education, to believe in herself that much in the face of strong resistance toward women in science at the time, and then to be willing and able to do the kind of lab work that she did. And then she married the right person. She and her husband, Pierre Curie, worked together when she started to do her doctoral research on this new discovery of physicist Henri Becquerel's, uranic rays.

This was the radiation coming from uranium decay.

Right. This was a new thing, and nobody was paying attention to it because everybody was more interested in x-rays in 1896. And Curie thought she'd go after the less exciting topic; there were 1,000 papers already written about x-rays, and nobody was doing anything with uranic rays. So that was the right time.

It's amazing to me that she entered this field at this time and then had her first child just a year later, in 1897. I'd assumed,

Illustration by Shideh Ghandeharizadeh before I read the book, that the children came well after she'd established herself as a scientist.

This is a very female story. She had two children; she had a miscarriage; she had trouble nursing. Some of the women who came to her lab stopped working when they got married and had children. It's been more than 100 years, and that's still true for many women in science. I really wanted to meet those issues directly in the book because I think it's so important for young women to read about other female scientists and how they managed.

Did Curie actively set out to recruit more women into science?

I don't think she was specifically looking to hire women, but what was different about her was that she had nothing *against* hiring them. So that was big, and then again she was so prominent that she attracted them and inspired them. There are a couple of women in the story who were much younger and grew up hearing about her, which made them think, "Oh, I could be a scientist, too." And the amazing thing to me is how she still has that effect. She's been dead for almost 100 years, but she is still an inspiration—and not just to women who go into science but to women in a variety of fields.

What do you think most people get wrong about Marie Curie?

You'll often hear that she didn't really do anything: it was all Pierre, and she was just his assistant. Pierre himself was on record debunking that, but nobody listened.

Another criticism was, "She used her hands but not her head. She was very involved in doing all of this very difficult chemical extraction, which required repetition of many steps, and that was what she was good at." That is also a very familiar trope about women in science: that women do this grunt work, the boring things, and the men just have aha! moments 24 hours a day.

That kind of attitude is just one aspect of the type of resistance Curie faced. What was the climate like at the time for women in science?

She was operating in this environment of huge sexism. She was barred from the French Academy of Sciences. Even though she had a lot of support, they did not vote her in, and to be published in their weekly proceedings, to present your work, you had to be a member. So she was constantly having to ask friends to present the work of the people in her lab, which was an enormous embarrassment. She was the premier authority on her subject, and she didn't have the standing in the professional community that she deserved. And then later her daughter tried several times to get voted into the academy. She was also a Nobel Prize winner, and she couldn't get in, either. So, yes, there was a lot of sexism, a lot of barricades, but she broke through most of them.

Beyond promoting individual women in science, how do you think Curie changed science for women after her?

We're talking about the early 1900s, so physics altogether was at an inflection point, and she was, for three decades, the only woman in the room at these important Solvay Conference meetings [a groundbreaking series of physics congresses that began in 1911]. So she knew all the top physicists: Ernest Rutherford, Albert Einstein, Enrico Fermi, Niels Bohr, everybody. She knew them personally, and I think she normalized some of that for them—that "oh, yeah, women do this, too," which might not have occurred to them. So I think, by her presence, she had an effect on her peers.

You are* Scientific American*'s poetry column editor. Is there any connection between Curie and poetry?

Well, being Polish and being in a family that was very nationalistic, very proud of its Polish heritage, she grew up on three very famous Polish poets: Adam Mickiewicz, Zygmunt Krasiński and Juliusz Słowacki. Her family also had a tradition of writing verses on this or that occasion, and she wrote a couple of poems. She wrote about her life as a student when she was first in Paris. I don't think she ever wrote any poems about her work. And there have been a lot of poems written about her. Even Adrienne Rich wrote a poem about Madame Curie.

The Roundest Object in the Universe

Finding a perfect sphere is actually pretty difficult

BY PHIL PLAIT

EVERY NOW AND AGAIN I'll get a weird thought in my head that sits there demanding an answer. Sometimes it's trivial, and sometimes it sounds silly but then leads to some fun insights. This time my brain decided to fixate on a simple question: What's the roundest object in the universe?

By that I mean, what is the most spherical object we've ever found—not necessarily the smoothest but the most symmetrical, where every point on its surface is the same distance from its center? (That's the definition of a sphere, after all.)

Lots of big things are round, and that's no coincidence. Gravity is to blame. As a cosmic object grows, usually by accumulating gas or via collisions with other bodies, its mass increases—and therefore its gravitational field increases, too. At some point the gravity gets so strong that anything sticking up too high will collapse, a process that eventually drives the object to become spherical. This mechanism is part of our lives on Earth: a mountain that gets too tall will crumble, and you can pile sand only so high at the beach before it will topple. Every time an astronomical object undergoes this kind of change, it becomes more smooth, more spherical.

This property emerges for objects once they grow to roughly 400 kilometers across, depending on what they're made of. So almost any discrete body with this diameter or larger will tend to be nearly spherical: big asteroids, moons, planets and even stars.

So which of these are the most geometrically perfect orbs? I poked around quite a bit, thinking of every kind of astronomical object I could, and in the end the answer I got was a surprise: the sun—yes, our nearest star!

Stars in general are quite round, but even the roundest ones deviate from being an ideal sphere. The main source of this departure is rotation because it creates centrifugal force.

Despite what you might have heard, centrifugal force is indeed real within a rotating reference frame—that is, if you're on a curving trajectory, this force makes it feel like something is pushing you outward. If you're in a car making a left turn, for example, you feel like you're being thrown to the right, to the outside of the turn.

For spinning spheres, centrifugal force is maximized at the equator, where the rotational speed is highest. The amount of the force depends on the size of the object and how fast it's spinning—bigger ones experience more force, and faster spins increase the force as well.

The sun is big, no doubt: more than 100 Earths could fit across its 1.4-million-kilometer-wide face. But at the same time, our star spins slowly, taking roughly a month to rotate once. This sedate spin is what may make it the winner of the roundness contest.

The sun's surface gravity is quite strong, about 28 times that of Earth—if you stood on its surface (and avoided being instantly vaporized), you'd weigh 28 times more than you do on Earth. But the centrifugal force at the solar equator is much weaker; the outward force you'd feel from our star's spin is only 0.0015 percent the force of gravity pulling you down right now. No wonder the sun is so round.

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Precisely measuring how round the sun is, though, turns out to be hard. It doesn't have a surface quite like Earth does; it's gaseous, so the material inside it gets less and less dense the farther away it is from the center. Near the "surface," however, the density drops so rapidly that from Earth the sun's edge appears sharp. Measuring the sun's size from the ground is hard because Earth's air is turbulent, smearing out the view of that edge. So to get a really good look at the sun's sphericity, astronomers turned to nasa's Solar Dynamics Observatory, a space-based astronomical sun telescope.

By taking very careful measurements, they found that the sun's oblateness—how much it is flattened at the pole versus the equator—is incredibly small, with a ratio of just 0.0008 percent. That means the sun is 99.9992 percent spherical. These results were published in the journal *Science Express.*

That's dang round. Weirdly, the scientists also found that this ratio doesn't seem to change with the sun's magnetic cycle. Right now we're at the peak of the strength of the sun's magnetism, which waxes and wanes on an 11-year cycle. But this powerful force doesn't seem to bother the sun's unbearable roundness of being at all.

I'll note that another solar system body is nearly this round: Venus—and for the same reason. Venus is an extremely slow spinner; it takes about 243 days to rotate once. That means the centrifugal force at its equator is very small indeed, and in fact, observations indicate the polar and equatorial widths of the planet are exactly the same to within measurement error.

This attribute makes it arguably rounder than the sun in principle, although in reality, it has surface-elevation variations of several kilometers, and so to scale, it's not as round as our star. (Earth's oblateness is about 0.3 percent because our planet rotates much faster than these other bodies.) That's true for planets in general, so Venus is neither sphere nor there.

Other stars, though, can be shockingly aspherical. One reason is that some rotate so rapidly that the centrifugal force at their equator is enormous; the bright star Altair is spinning so quickly that material at its equator is screaming along at nearly a million kilometers per hour. As a result, its equatorial diameter is 20 percent

Venus is seen (*at top*) transiting the sun. Both objects are almost perfectly round—more spherical, in fact, than most other celestial bodies precisely measured by astronomers.

LinP74/Getty Images

wider than its diameter through the poles.

Other objects may be even rounder than our sun, but they are so far removed from our probing instruments that we can't precisely discern them. Some, however, we can somewhat reliably scrutinize from first principles—such as neutron stars, which, as a class, are true heavyweight contenders for Most Spherical Object. Each of these überdense orbs is the remnant of a star more massive than the sun that underwent a supernova; the core of the star collapsed to essentially become a ball of neutrons a mere two dozen kilometers across. Neutron stars are so dense that their surface gravity can be billions of times Earth's.

Various forces can cause some neutron stars to spin extremely rapidly, however; one star called PSR J1748-2446ad spins a whopping 716 times per second! That's higher than the rate of the blades in a kitchen blender. The centrifugal force at the star's equator, despite the orb's cosmically Lilliputian size and Brobdingnagian gravity, is almost enough to rip it apart.

Over time, though, a neutron star's spin slows, and one that formed early in the universe could now be nearly static. In that case, the intense gravity (I'd weigh upward of a billion tons standing on one) would be enough to crush the neutron star to a very nearly perfect sphere, perhaps with the difference in flattening between its equator and poles measured in widths of atoms. Will astronomers ever find one this spherical? Maybe, once they get around to it.

This question is more than just playful, though. It's difficult to understand the internal structures of many cosmic objects because we can't visit them, and their pressures and temperatures can be far too great even to replicate in a laboratory. By measuring the exact shapes of things like the sun and the planets, we learn more about what happens under their surface and discover what makes them tick.

Astronomers love to figure this kind of thing out, even when it means asking what sound like silly questions. That part is fun, sure, but finding the answer is when we really have a ball. ●

How Expertise Improves Concentration

Practice in a task strengthens our ability to think deeply, a skill the brain may generalize

BY HANNA POIKONEN

THINK OF THE LAST TIME you concentrated deeply to solve a challenging problem. To crack a math puzzle or determine a chess move, for example, you might have had to screen multiple strategies and approaches. But little by little, the answer to the conundrum came into focus. Numbers and symbols may have fallen into place. It might have even felt, at some point, like your problem effortlessly resolved itself on the blackboard of your mind.

In recent research, my colleagues and I investigated the neural mechanisms underlying these experiences. Specifically, we wanted to understand what happens in the brain while a person engages in abstract and demanding thought—so we designed a study involving math expertise.

Mathematical thinking relies on an ancient brain network located in the parietal regions, at the top and center of the brain's outer folded cortex. This network helps us process space, time and numbers. Previous studies on neurocognition in mathematics focused on what happens in the brain while people consider problems that take a few seconds to solve. These studies have helped illuminate brain activity that supports focused attention and a special form of recall called working memory, which the brain uses to keep numbers and other details top of mind in the short term.

In our work, we used longer, more complex math

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Illustration by Thomas Fuchs

challenges that had to be solved in multiple steps. These problems are more akin to the tricky puzzles that mathematicians must tackle regularly. We found that people with more experience in mathematics enter a special state of deep concentration when thinking about hard math problems. Understanding that state could someday help scientists understand the power of concentration more broadly, as well as the possible trade-offs of off-loading our problem-solving to our devices.

For our experiment, we recruited 22 university students—at both the graduate and the undergraduate level—who were in math or math-related programs, such as physics or engineering, along with 22 students in disciplines with minimal to no quantitative emphasis, such as physiotherapy or the arts. We determined each student's verbal, spatial and numerical intelligence quotient (IQ), as well as their level of math anxiety.

The students watched step-by-step presentations that explained how to solve several challenging math problems. Throughout this demonstration, the subjects wore caps covered with electrodes so we could track the electrical activity in their brains. After each presentation, they reported whether they thought they had understood the information and how engaged they felt during the experience. We also encouraged the participants to watch the demos carefully by telling them they would have to explain the problem afterward.

We found that the students with greater math expertise showed markedly different brain activity than those with less. For example, those whose coursework involved little mathematics showed more signs of complex activity in the prefrontal cortex, an area just behind the forehead that is engaged in all kinds of cognitive efforts. This finding may reflect how hard these participants were working to understand the various steps of the complex math demonstrations.

But things really got interesting when we turned to students who engaged in quantitative thinking regularly. We noted significant activity that appeared to link the frontal and parietal regions of their brain. More specifically, these areas exhibited a pattern of activity that neuroscientists call delta waves. These very slow waves of electrical activity are typically associated with states such as deep sleep. Of course, these students were wide awake and deeply engaged—so what was going on?

Very slow delta brain waves are typically associated with deep sleep, not with intense concentration. So what was going on?

Some recent research suggests these "sleepy" delta waves may play a crucial role in the cognitive processing that supports deep internal concentration and information transfer between distant brain regions. For example, some studies show that large-scale delta oscillation emerges among experienced meditators when they enter meditative states. One reason that brain-activity patterns during meditation, mathematical problem-solving and sleep resemble one another might be that, in each case, the brain needs to suppress irrelevant external information and unneeded thoughts to concentrate on the task at hand. (Indeed, even sleep can be a busy time for the brain. Sleep research has revealed deep sleep's irreplaceable role in memory consolidation; slow-wave sleep retraces the neural patterns that were previously activated during a learning task.)

In fact, we suspect that the long-distance delta oscillation we observed may play a central role whenever people are immersed in contextual and complex problem-solving. For instance, we have found that dancers and musicians show similar delta waves when watching dance or listening to music, which suggests that engaging brain networks in this way could be useful for many tasks involving concentration. Most likely when people who have extensive experience in a task are profoundly engaged in that effort, these same slow delta waves are involved, even if the specific brain networks vary. It's also possible that this state of immersive concentration is generalizable: develop this way of thinking in one domain, whether it's tackling trigonometry or playing the violin, and it could help you in others. We'll need to investigate this idea further to be sure.

Although our experiments involved students and not, say, champion mathematicians or Nobel laureates, the differences in brain activity that we observed are still a testament to the power of practice in expertise. Our student participants did not significantly differ in their IQ or level of math anxiety, for example. Instead repetition and deliberate or intentional study helped some of these graduate and undergraduate students become more efficient masters of quantitative thinking.

By the same logic, these findings hint at a trade-off that people should keep in mind—particularly as artificial intelligence and other tools offer tantalizing shortcuts for various forms of problem-solving. Each time we off-load a problem to a calculator or ask ChatGPT to summarize an essay, we are losing an opportunity to improve our own skills and practice deep concentration for ourselves. To be clear, technologies can boost our efficiency in important ways, but the seemingly "inefficient" hard work we do can be powerful, too.

When I consider how frenetically people switch between tasks and how eagerly we outsource creativity and problem-solving to AI in our high-speed society, I personally am left with a question: What happens to our human ability to solve complex problems in the future if we teach ourselves not to use deep concentration? After all, we may need that mode of thought more than ever to tackle increasingly convoluted technological, environmental and political challenges. ●

It's All Coming Together

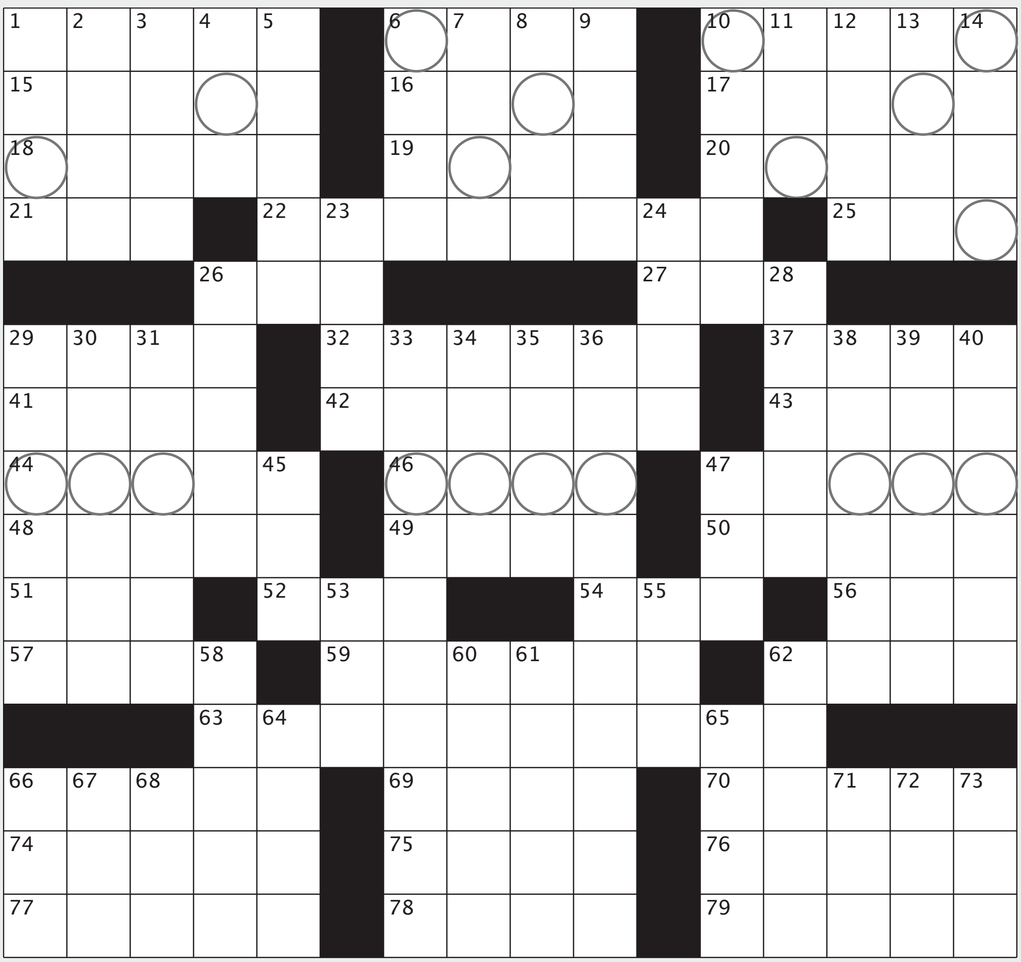
BY AIMEE LUCIDO

Across

1 Latin American cornmeal cake
6 CBS procedural franchise
10 Acrylics, for example
15 Occam's ___ (scientist's principle of parsimony)
16 Big name in footwear
17 John Corbett's *Sex and the City* role
18 Scientist Marie who encouraged generations of women to go into science (*page 78*)
19 Some July and August babies, astrologically
20 Large member of the violin family
21 In the style of
22 Source of an ancient slab discovered in Earth's mantle under the Pacific Ocean (*page 20*)
25 Take some courses?
26 Fishy bagel topping
27 Bank statement (abbr.)
29 Something that a new "electronic tongue" can discern the brand of (*page 12*)
32 Invites
37 Forever, seemingly
41 Bond's alma mater
42 Like the labyrinth of Knossos
43 Marine ___ (mixture of plankton carcasses, excrement, and molt particles that constantly drift through the ocean)
44 Large sea snail
46 Hibernation spots
47 Solid, liquid or gas, for example
48 Mathematician Penrose
49 Small furry *Star Wars* series character
50 Adjective that describes the sun more than it does any other known object in the universe (*page 79*)
51 Right-angle shape
52 Texting format (abbr.)
54 Kangchenjunga and Denali, for two (abbr.)
56 Full understanding of what makes the cosmos tick, for short
57 Merch-table tops
59 Tomato-based dips
62 Pillow fill
63 Blob in cellular biology that self-assembles as its molecules cluster together, a phenomenon that is depicted in a literal way in this grid (*page 22*)
66 Aquafina rival
69 "Oh, crud!"
70 Hyped
74 With 76-Across, substance that a 63-Across resembles
75 Passed-down stories
76 See 74-Across
77 Early text messager
78 Watchful one
79 Chip away at

Down

1 Medieval Spanish chest
2 One of Cuba's Castro brothers
3 *New York Times* opinion writer Klein
4 Hawaiian taro dish
5 "Am not" retort
6 Disney lion voiced by Beyoncé
7 Musical range indicator
8 Megan Thee Stallion to the Hotties
9 Mid
10 Iridescent material that inspired a superstrong glass composite
11 French exclamation of pain (*page 16*)
12 Not doing anything
13 Singsong syllables
14 Substance added to Alexander Fleming's petri dish
23 Admissions hurdle
24 Take too much of, briefly
26 Jouster's weapon
28 Basil-based sauce
29 Something kept because of an overestimated harsh judgment
30 Peter of *Lawrence of Arabia*
31 USB drive insert
33 One way to ride a horse
34 Fully understood
35 Prefix with "gram"
36 British game show named for a difficult boss
38 Proceeding robotically
39 "It'll have to wait"
40 Most populous Nordic country
45 There are 24 in a day (abbr.)
47 Fourth-year HS students
53 Web portal with a butterfly logo
55 LAX wand wielders
58 Weighing device
60 "Bad, Bad" Brown of song
61 It's a trap!
62 Take exception
64 Parallel-banded variety of chalcedony
65 Scotch roll stuff
66 Approx.
67 Compete (for)
68 Feeling queasy
71 Accumulation for a vacation, for short
72 When to expect takeoff, briefly
73 Purchase for purple hair



For the solution, visit www.ScientificAmerican.com/games/science-crosswords

Fear in the Air

The revival of aerobiology and our reluctance to face airborne threats

BY PITCHAYA SUDBANTHAD

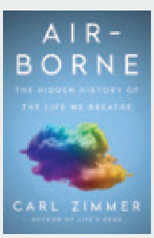
Buena Vista Images/Getty Images

NONFICTION The air around us is more alive than we might care to think. What seems like an in-between void is really a far-reaching ecosystem populated by life-generating cells, from fungal spores to plant pollen, and organisms at the tiniest scale. We breathe in and out rivers of beings, and until the devastation of COVID-19 reminded us of the intricate intimacy between humanity and the so-called aerobiome, we often did so without much awareness.

The difficulty of directly observing life in the air has long shrouded its study with mystery and maintained inertia in its body of knowledge, explains journalist Carl Zimmer in his latest book, *Air-Borne: The Hidden History of the Life We Breathe.* Aerobiologists who think of the atmospheric environment as a habitat sometimes lament the invisibility of its biodiversity. But the field wasn't always so underappreciated.

The air once ruled Western science. Zimmer charts the vagaries of biological and medical knowledge, where wild, dissenting beliefs can become accepted scientific facts and then return to obscurity. Miasma theory, dating to the texts of Hippocrates in the fifth century B.C.E., survived through the preservative labor of Syriac monks to become medieval Europe's prevalent explanation of disease. "Bad air" emanated from foul rot to invade the body and disrupt the humors, causing illnesses from cholera to tuberculosis. The theory lingered well into the 19th century, when sanitarians, including Florence Nightingale, sought to prevent sickness by changing hospital bedding and opening windows to remove corrupting odors.

Germ theory, however, was in ascendance. After Antonie van Leeuwenhoek's innovations with the microscope in the late 1600s, scientists could more easily observe microorganisms everywhere, including in the air. In the late 1800s Louis Pasteur became fixated on showing how far microbes traveled; he even climbed into the Alps to collect air samples. The emerging contagionists believed germs, not fumes, caused sickness.



Air-Borne: The Hidden History of the Life We Breathe
by Carl Zimmer. Dutton, 2025 ($32)

This development was to the chagrin of a medical establishment that labeled contagionists "the drinking-water faith" and dismissed evidence that comma-shaped bacteria were behind cholera epidemics. Zimmer sets up the long, heated and ultimately tragic contest in the 1880s between germ theorist Robert Koch and miasmatist Max von Pettenkofer as the showdown that led to the diminishment of aerobiology in modern medicine.

But downfall from prominence did not signal the end of scientists curious about the airborne. With exhaustive detail and impressive breadth, Zimmer chronicles the multigenerational comeback of a nearly lost science. At the dawn of the 20th century, as American farmers suffered disastrous crop losses from wheat rust, the U.S. government became interested in surveying the aerial ranges of spores. Plant pathologist Fred Meier, a former watermelon expert, led the research, at times collaborating with Charles Lindbergh and Amelia Earhart to capture air samples with high-flying petri dishes.

Meier's place at the helm would eventually be inherited by William Firth Wells, a former water-sanitation scientist who repurposed his attempted method for regenerating oyster populations with filtered eggs to create an air centrifuge for capturing pathogens. It was largely the ceaseless work of Wells and his wife, Mildred, a physician and epidemiologist, that propelled the science of airborne life through the 20th century. The path was not easy for the Wellses, as the medical establishment did not welcome the idea of pathogens traveling long ranges in the air in conditions that were not easy to control.

But, as Zimmer deftly shows, a vastly changing world made the revival of aerobiology seem fated. World War II, the cold war and the post-9/11 era fostered paranoia that enemies could be found everywhere, and what's more fearsome than invisible airborne toxins and viruses? Those fears allowed for worldwide experimentation with air-released biological weapons and the creation of larger, more horrific "infection machines." Zimmer writes about disturbing exposures to lethal pathogens that were not always intentional or voluntary.

This anxiety about the proliferation of human-made bioweapons proved less warranted than worries over naturally occurring diseases, such as the SARS and H1N1 outbreaks in the early 21st century. An age of rapid economic and social globalization, as well as the expansion of dense, closely quartered cities, only made the study of airborne pathogens more urgently necessary.

Yet even as the availability of DNA sequencing and improved computer models helped to confirm the reality of airborne pathways, authorities often appeared reluctant to address it. Zimmer connects institutional obstacles confronted by the Wellses to challenges faced by defiant scientists who called themselves Group 36 during the recent COVID pandemic: inconsistency and a lack of clarity from the World Health Organization, alongside political pressures. *Air-Borne* shows how difficult it is to harmoniously coexist with oceans of unseen microbes in the air, but the greater threat to our existence, Zimmer argues, may come from our own close-mindedness.

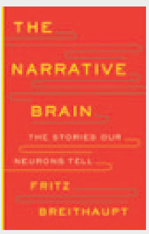
Pitchaya Sudbanthad is author of the novel *Bangkok Wakes to Rain* (Riverhead Books, 2019), which was selected as a notable book of the year by the *New York Times* and the *Washington Post.*

Why Stories Endure

Narratives can be a trap—but they also can be rewritten

NONFICTION Humans are storytelling animals. We narrate our lives as soon as we can speak and populate those tales with classic characters: heroes, mentors, villains. In *The Narrative Brain,* cognitive scientist Fritz Breithaupt explores why we render the world in stories—and how the rewards of narrative thinking keep us spinning out yarns.

Despite its title, very little of *The Narrative Brain* is about biological wetware, the neurons and synapses that make storytelling possible. Breithaupt is less interested in brain-scan findings than in how stories evolve as they move between tellers and what that evolution reveals about the purpose stories serve.



The Narrative Brain: The Stories Our Neurons Tell
by Fritz Breithaupt.
Yale University Press, 2025 ($35)

Breithaupt's inquiry draws on "telephone game" studies that ask each participant to tell a story in their own words, then pass it to someone else who does the same. These ongoing exchanges, he argues, help to illustrate what narratives do for us. Disjointed tales grow more coherent and logical as they move down the line, showing how storytelling brings sense and order to a complex, chaotic world. Stories' emotional thrust, however, stays much the same in repeated tellings, suggesting that the feelings they evoke (say, joy when a thwarted romance works out) are core to their appeal. We narrate our lives, and inhale stories about other lives, for much the same reason we frequent bars and poker rooms: the frisson of anticipated reward.

Echoing Jonathan Gottschall, author of *The Story Paradox* (Basic Books, 2021), Breithaupt warns that our addiction to narrative—however fulfilling—can close off possibilities outside the borders of our pet stories. Casting ourselves as victims tempts us to stay in that role, and when we want to believe epic-style justice will triumph, we may not accept realities that veer in a different direction.

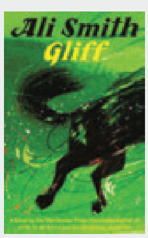
Even so, Breithaupt remains a narrative optimist. Our storytelling knack, he contends, primes us to master what he calls "playability": rendering endless possible futures in story form, which helps us anticipate and plan for the best of these futures. "Narratives can be the medium of our unhappiness," he writes, "but they are also the means of escaping it." He includes few details about how to achieve this escape; unlike the classic stories that inspired it, *The Narrative Brain* does not build to a clear resolution. Yet its very open-endedness—its invitation to reimagine ill-fitting stories—makes it a timely corrective to our fierce zest for certainty. *—Elizabeth Svoboda*

Lost in Surveillance

Surviving a familiar dystopia

FICTION In a totalitarian version of Great Britain, hovering somewhere in an adjacent present or near future, people are either worker drones or undesirables deemed "unverified" by a nebulous gray authority. This is the background of *Gliff,* a new novel from award-winning Scottish writer Ali Smith. Foreground and background are almost indistinguishable here. They fade through and past each other in this matter-of-fact, wordplay-loving liberation story, which is full of explicated and dissected terms, incidental etymologies, and puns. Smith's didacticism is camouflaged in conversation, a series of clever lessons on the small histories of words and the mutability of language.

In the foreground, two children tumble through a cascade of abandonments, struggling to stay fed and find their footing in a city where, during the night, red lines may get painted around the place where they're sleeping. They get separated first from the loving whistleblower mother who raised them, then from the man to whom she entrusted them, and finally and mysteriously from each other. Woven into this tapestry in an artful hodgepodge are glancing critiques of xenophobia, capital and soulless technocratic overlords—all keenly relevant to 2025 America, where, as the specter of mass deportation looms, it's all too easy to read Smith's dystopia as a fairly accurate description of the time we find ourselves living in.



Gliff
by Ali Smith.
Pantheon, 2025 ($28)

But "dystopia" is probably a misnomer. Smith's fictional decor features many imagined stylings, such as the literal lines of red paint and the "Supera Bounder" machines that draw them, but the surveillance state it conjures isn't far removed from already existing forms of institutionally sanctioned observation and oppression. In the U.K., closed-circuit TV cameras are ubiquitous; in the U.S., private corporations have almost unlimited access to personal data; throughout the Global North, immigrants and refugees are increasingly being targeted for rejection or expulsion by hostile governments.

What *Gliff* suggests is that dystopia is no longer a counterfactual. It is now manifestly present and far-reaching, and it's up to us to cast off our chains. *—Lydia Millet*

Illustration by Elliot Lang

The Astronaut Club

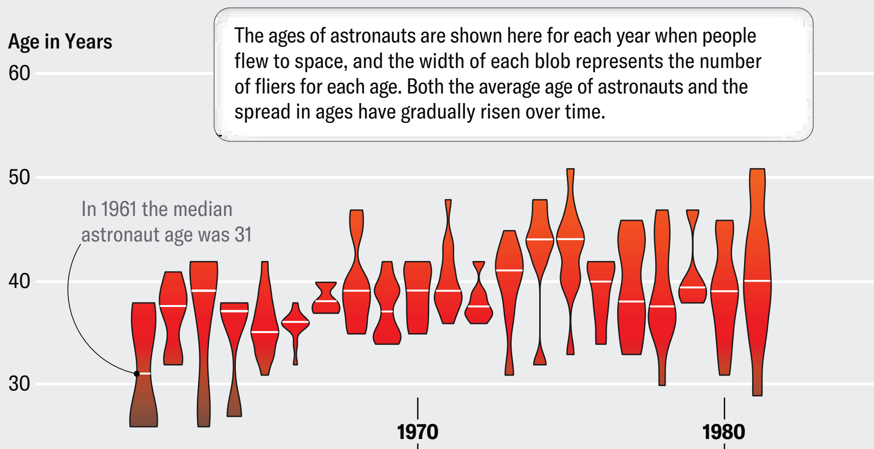
A close look at every person who's ever gone to space

TEXT BY CLARA MOSKOWITZ
GRAPHIC BY ZANE WOLF

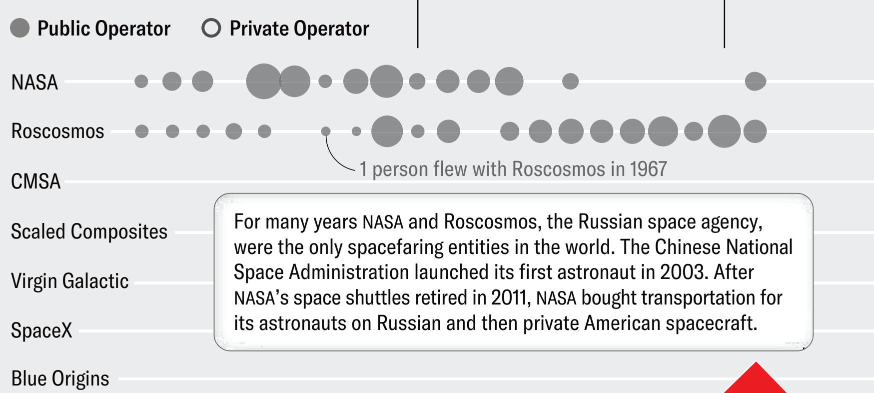
IN 1960 NO ONE had ever traveled beyond Earth. Now more than 700 people have flown past the 50-mile-high mark that was considered the boundary of space when spaceflight first got started. At that time, the Soviet Union and the U.S. were the only teams, and military men around 30 years old were practically the only players. Since then, astronauts have diversified in many ways: men and women from 47 countries have reached space, including residents of every continent, most in the employ of space agencies and some with private companies. Diversity hasn't been a straightforward march, though: in 1963 the U.S.S.R. launched the first woman into space, but in subsequent years only five more female cosmonauts flew in total, whereas dozens of male cosmonauts went up each decade.

The number of space visitors peaked in the 1990s, when NASA flew an average of six space shuttle missions a year, each usually carrying five to seven astronauts. The first shuttle launched in 1981, but the program took a nearly three-year hiatus after the *Challenger* disaster in 1986. The shuttle fleet was grounded again for more than two years when *Columbia* broke up on its return trip to Earth.

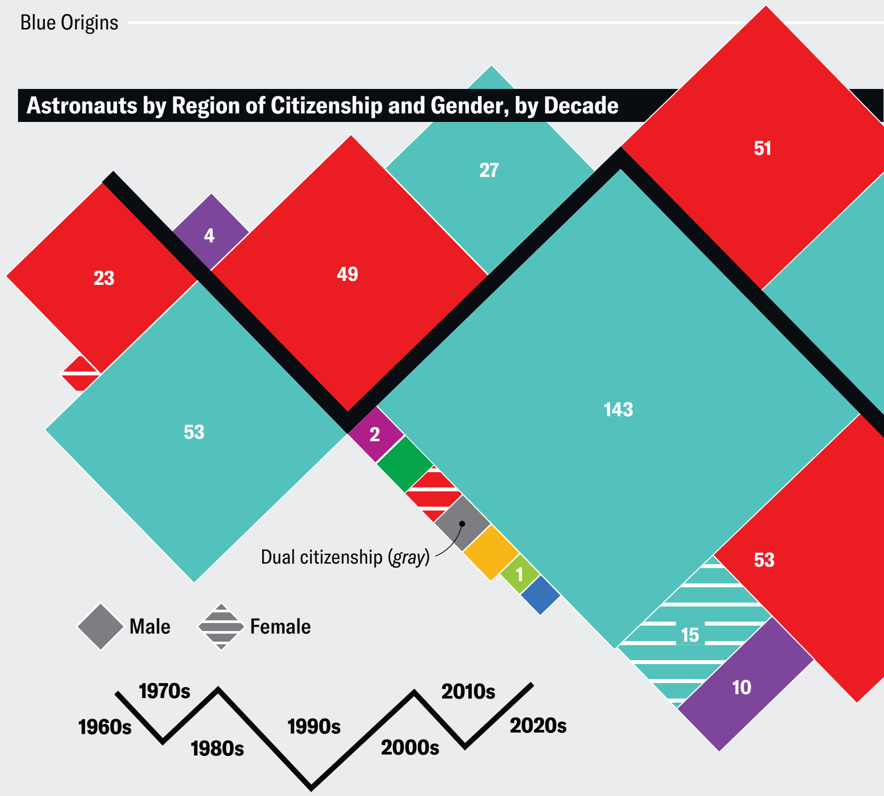
Annual Age Distributions of Astronauts Sent to Space



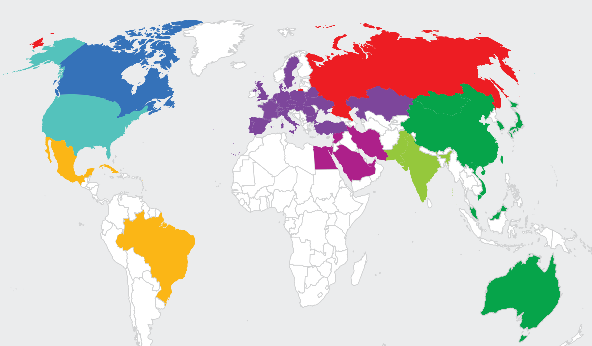
Astronauts Sent to Space by Operator over Time

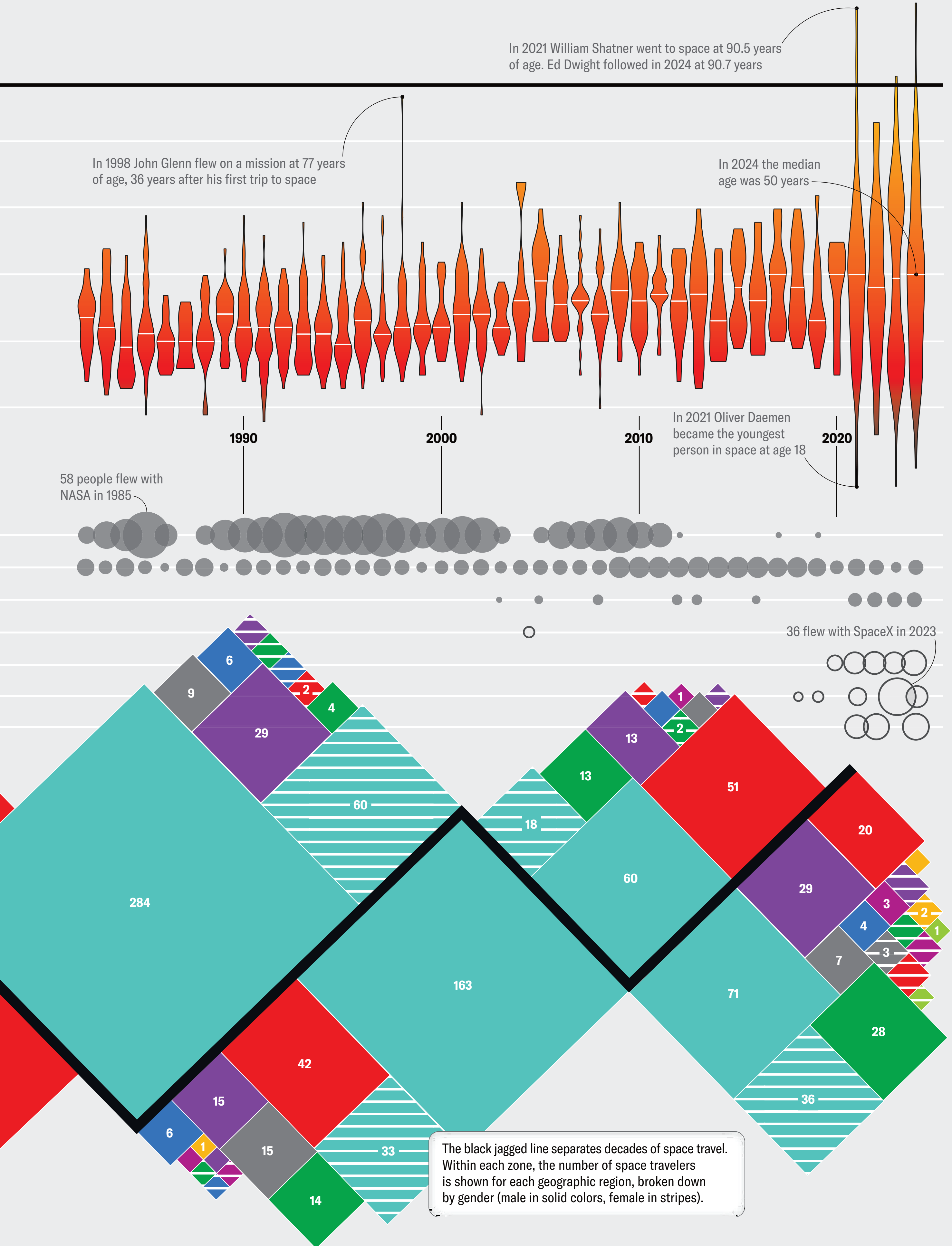


Astronauts by Region of Citizenship and Gender, by Decade



Region
- Canada
- U.S.
- South Asia
- Russia
- East Asia and Pacific
- Europe and Central Asia
- Latin America and Caribbean
- Middle East and North Africa

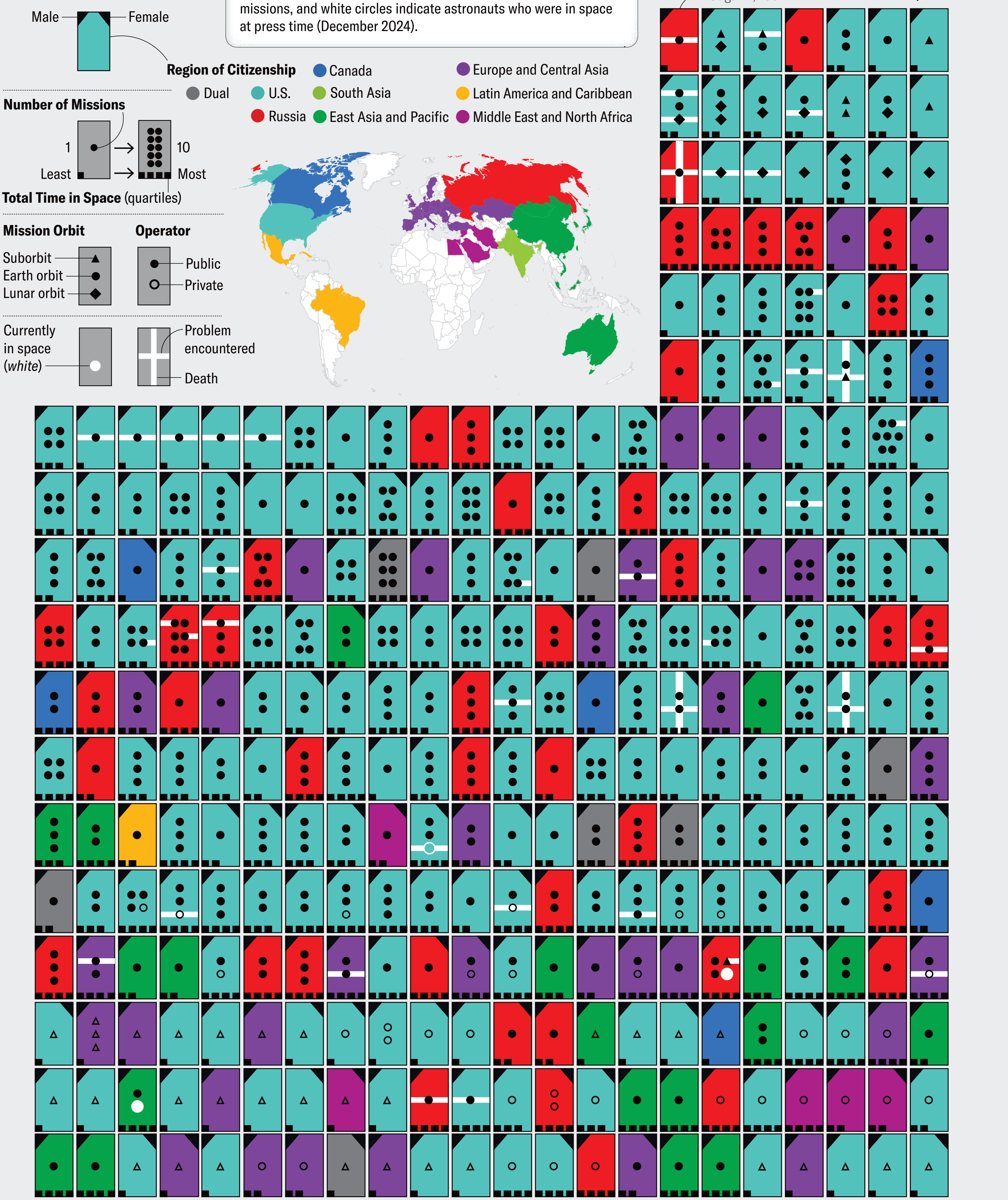



In 2021 William Shatner went to space at 90.5 years of age. Ed Dwight followed in 2024 at 90.7 years
In 1998 John Glenn flew on a mission at 77 years of age, 36 years after his first trip to space
In 2024 the median age was 50 years
1990
2000
2010
2020
In 2021 Oliver Daemen became the youngest person in space at age 18
58 people flew with NASA in 1985
36 flew with SpaceX in 2023
6
9
2
4
29
60
284
18
13
1
13
2
51
20
60
163
29
3
2
4
1
3
7
71
28
42
15
6
1
15
33
14
36
The black jagged line separates decades of space travel. Within each zone, the number of space travelers is shown for each geographic region, broken down by gender (male in solid colors, female in stripes).

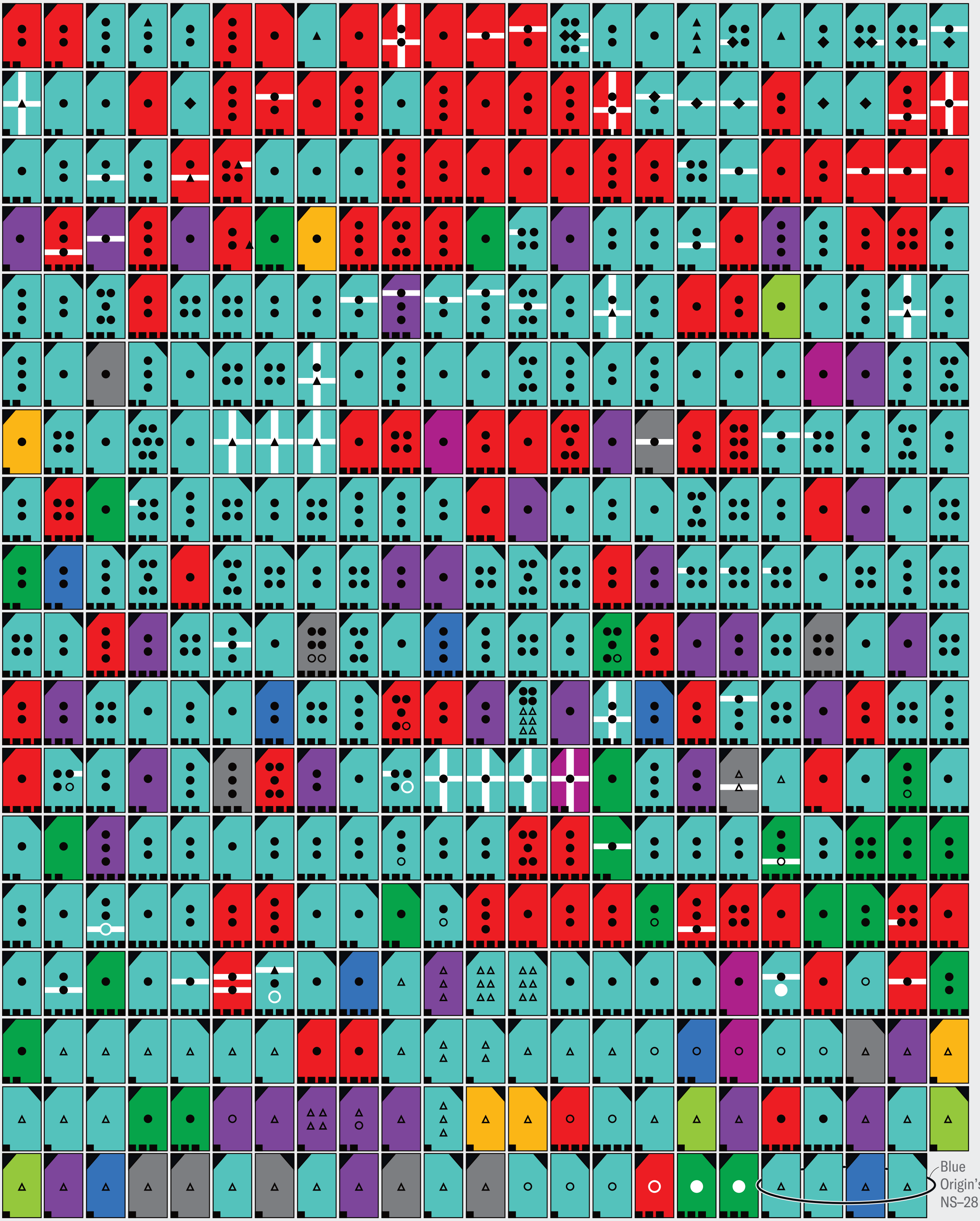
Each tile represents an individual space flier. Color and tile symbols signify each person's region of citizenship, gender, number of missions, duration in space, type of flight, and public or private status. Vertical white lines mark astronauts who died on space missions, and white circles indicate astronauts who were in space at press time (December 2024).

Mission Data for Individual Astronauts

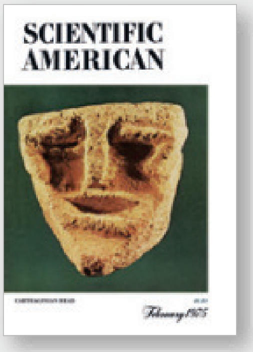
Each rectangle represents an astronaut. Rectangles are



organized by first date in space, from Yuri Gagarin on April 12, 1961, in the top left to the crew of Blue Origin's NS–28 mission on November 22, 2024, on the bottom right.

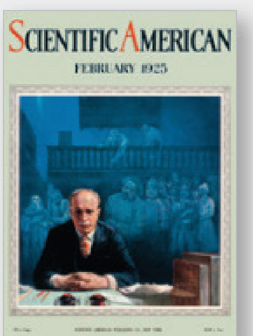


50, 100 & 150 Years



RADICAL REVISION OF CONTINENTS AND POLES

1975 "Of the various hypotheses that preceded the modern theory of plate tectonics, one version propounded by Alfred Wegener early in the 20th century stands out. Wegener had access to only a small part of the information available today, yet his theory anticipated much that is now fundamental, including the movement of the continents and the wandering of the poles. When his view did replace the older model (in the 1960s), the change represented a radical revision of a well-established doctrine. In the interim, Wegener's theory had at best been neglected, and it had often been scorned. At the nadir proponents of continental drift were dismissed contemptuously as cranks."

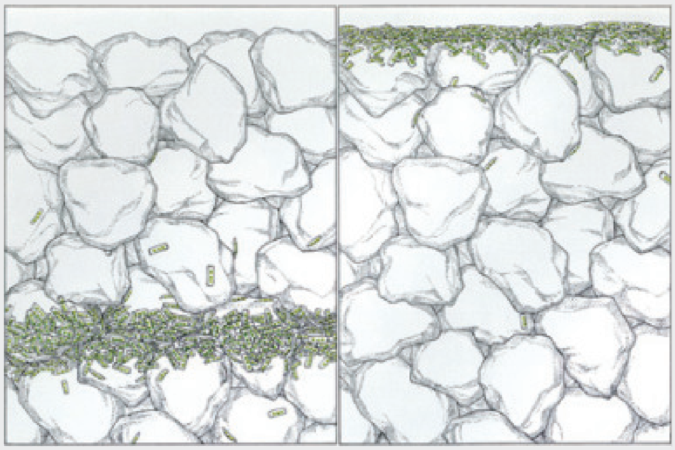


SPRING VEGETATION ON MARS

1925 "A series of photographs of Mars made by Slipher at the Lowell Observatory show in a very beautiful and convincing way how the dark regions grow larger and deeper in hue as the polar caps wane and the Martian spring advances. The dark markings on the opposite hemisphere, where autumn is changing to winter, are seen to fade. Slipher says, with reason, that the seasonal markings obey the law of change that we should expect of vegetation. Whether or not vegetation actually does cover much of the planet's surface is harder to determine. If the chlorophyll of Martian vegetation is similar to that of terrestrial plants, it should reflect deep red light strongly, and the dark markings should show bright when photographed through a suitable screen. Nothing of this sort has been observed. But the test is not conclusive; many terrestrial plants do not show this peculiarity."

A FINE HUDSON RIVER ICE HARVEST

1875 "The Hudson River ice crop for 1875 has been harvested and is one of the largest and finest ever gathered. The blocks average 14 inches in thickness, and the total quantity secured is about two million tuns. This enormous supply will be chiefly consumed in the city of New York. It is brought down the Hudson River from the great ice houses, located at the water's edge, in large barges towed by steam directly to the ice carts, and then conveyed to private dwellings. From a quarter of a tun to a half a tun a month is a common supply for a small family. The price is from $15 to $30 a tun."



1975, Daily Micromigration: "The diatoms *Hantzschia virgata* reside about a millimeter below the surface of shoreline sand (*left*). During daytime low tides the organisms are propelled upward to the surface by mucus forced through pores at the end of their elongated, glassy cell wall (*right*). The diatoms remain in the sunlight, for photosynthesis, until moments before the sand is inundated by the returning tide."

Scientific American Vol. 232, No. 2, February 1975

NEVADA STREETS PAVED WITH GOLD

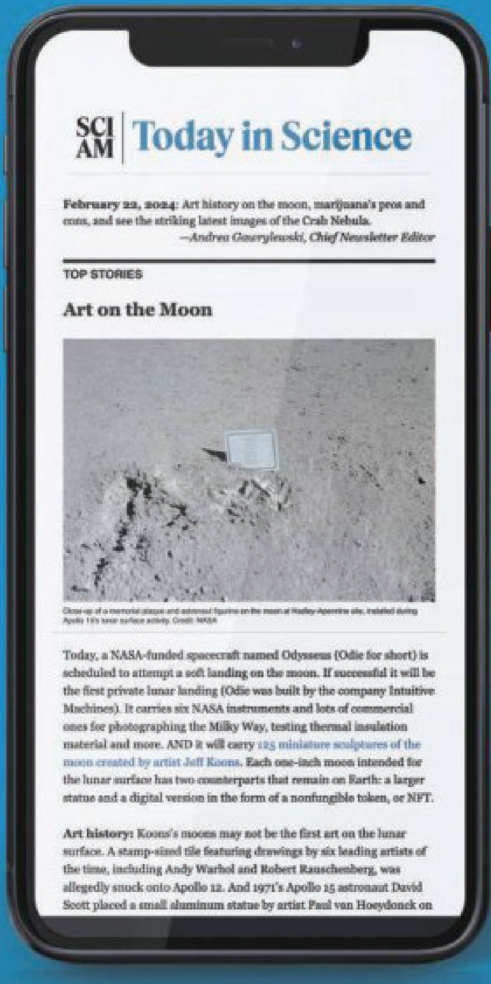
"The denizens of Virginia City, Nev., boast that the very mud of their streets is rich in silver and gold. The principal streets were macadamized with refuse ore taken from the mines in early days. Since then, they have been steadily dusted with rich ore sifted down upon them from passing ore wagons, making a surface so precious that an ounce or two of mud proved on assay to contain, to the tun: silver, $7.54; gold, $2.32; total $9.86. 'After this,' exults the *Enterprise* of that richly paved city, 'we may put on airs, even though our streets are villainously muddy occasionally, for the very mud on our boots contains both silver and gold.'"

Virginia City was a booming mining town in the mid-1870s, when population peaked at around 25,000. Population in 2020 was 787, according to the U.S. Census.

DO ANTS TALK?

"Ants have an impressive ability to communicate. Information of common danger is quickly spread throughout colonies numbering many thousands, the news brought by perhaps one or two spies. Their mode of communication has been a mystery, the most plausible hypothesis being that it was by a sort of fencing with antennae. But according to a report of Professor Landois to the Natural History Society of Prussian Rhineland, ants are provided with a sounding apparatus resembling that of the sand wasp. Although its pitch is generally inaudible to human ears, its range of tone may be ample for a fully developed language. The next thing in order is an apparatus for making inaudible sounds audible; then some enterprising student may give us a comparative grammar of formic idioms."

Scientists have long shown that ants communicate using chemicals called pheromones, which among other benefits helps them march single file in long lines. Yet in recent decades they have found that certain ant genera make noise, and even some ant pupae can communicate using sound.



SCI AM | Today in Science
February 22, 2024: Art history on the moon, marijuana's pros and cons, and see the striking latest images of the Crab Nebula.
—Andrea Gawrylewski, Chief Newsletter Editor
TOP STORIES
Art on the Moon
Today, a NASA-funded spacecraft named Odysseus (Odie for short) is scheduled to attempt a soft landing on the moon. If successful it will be the first private lunar landing (Odie was built by the company Intuitive Machines). It carries six NASA instruments and lots of commercial ones for photographing the Milky Way, testing thermal insulation material and more. AND it will carry 125 miniature sculptures of the moon created by artist Jeff Koons. Each one-inch moon intended for the lunar surface has two counterparts that remain on Earth: a larger statue and a digital version in the form of a nonfungible token, or NFT.
Art history: Koons's moons may not be the first art on the lunar surface. A stamp-sized tile featuring drawings by six leading artists of the time, including Andy Warhol and Robert Rauschenberg, was allegedly snuck onto Apollo 12. And 1971's Apollo 15 astronaut David Scott placed a small aluminum statue by artist Paul van Hoeydonck on