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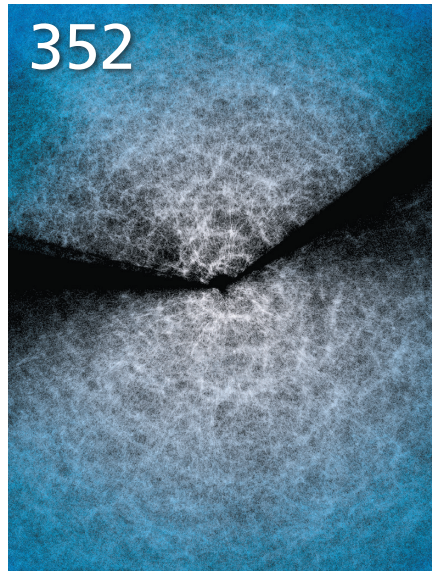
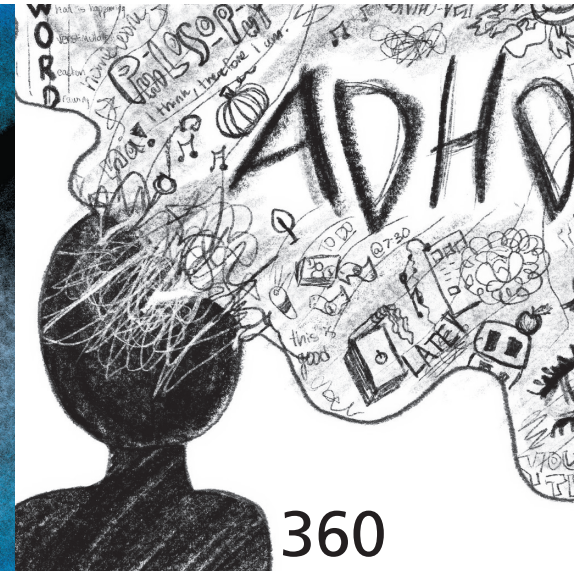
Scientists' Nightstand

From Sigma Xi

Feature Articles





The Cover

The large-scale structure of the universe was set by the tiniest of forces—quantum fluctuations—during the incredibly brief period of rapid expansion that occurred just after the Big Bang. These initial moments, the only period in which both quantum and gravitational dynamics have ever significantly interacted, created a gravitational noise still visible in the primordial light that astronomers call the cosmic microwave background (CMB). In "The Unlikely Primeval Sky" (pages 352–359), Craig Hogan explores our current understanding of the CMB and the information that can be derived from it, including the fact that our cosmos is strangely smooth and surprisingly flat compared to the vast majority of likely universes. Is this a fluke, or a call for new physics? (Cover art by Illustris Collaboration.)

A Life of Purpose

Caught in the Moment Photography

It seems amazing that it has been a century since the trial of *The State of Tennessee v. John Thomas Scopes*, yet the central question of what constitutes evidence-based science still remains under debate.

Scopes (*shown below, left, with attorneys*) was found guilty in that trial of violating Tennessee's Butler Act, which forbade the teaching of any theory that contradicted the Biblical story of the divine creation of humans. Scopes was fined, but his verdict was overturned on a technicality. The Butler Act was not repealed until 1967, and the Supreme Court ruled other state laws against the teaching of evolution to be unconstitutional in 1968.

Bryan College

However, as Robert T. Pennock details in this issue's Science and Engineering Values column, "On a Wing and a Prayer?" (pages 346–351), court cases continued. Pennock was an expert witness in the *Kitzmiller v. Dover Area School District* trial that concluded in 2005. That case centered on intelligent design, which proponents tried to argue in court was different from creationism. Pennock recounts how he and other expert witnesses were able to show that an intelligent design textbook that was central to the court case switched from using the terms "creationism" and "creationist" to "intelligent design" after a 1987 Supreme Court case ruled that teaching creationism as science was unconstitutional. In the Dover case, the judge also ruled that intelligent design could not be taught as science.

Pennock uses the example of aerospace engineering to highlight the point that including the divine in any evidence-based enterprise would be irresponsible. But as he notes, there's nothing about evolution that precludes a life of meaning and purpose. Indeed, although scientific research can be tough, most scientists find that their work is fulfilling, no matter what their personal convictions may be.

Scientists continue to show dedication to their research, despite significant ongoing U.S. federal funding cuts. Communication has always been central to the scientific process, and scientists have been looking for ways to make clear how these cuts will affect research. For several issues, we have been requesting letters from scientists to raise awareness as to why their research is important. There are more responses in this issue's Letters section (pages 323–324), and we are consistently impressed by the research and dedication of the scientists who write in. We encourage you to continue submitting your letters. As a reminder, please keep your letter submissions to no more than 300 words. Let us know if you would like us to keep your letter anonymous, or if you are comfortable sharing your name, your location, or both. Please note that as a nonprofit, *American Scientist* is not permitted to endorse any specific legislation or candidate, but we can support evidence-based science policy, so please keep your submissions nonpartisan. Focus your letter on why your work is important, effective, and worth carrying out. Send your submissions to editors@amscionline.org with the subject line "Science Is Important." Letters may be published in print or on our website, and may also be featured on social media. —*Fenella Saunders*

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Note from the Editors

In the July–August issue, we published a call for letters asking scientists to give brief explanations of their research and why it is important. We hope that these letters will bring awareness to the vital work of scientists and to the need for continued research funding. If you would like to submit a letter, please keep it to 300 words or fewer and email it to editors@amscionline.org with the subject line "Science Is Important."

My Science Is Important

To the Editors:
Imagine this: You've decided to bake a really fancy, really delicious cake. You fundraise to buy the ingredients: premium butter, cage-free eggs, and artisanal flour. You sift together the dry ingredients, stir in the wet, pour it all into a greased pan, and bake it. Once the cake is cooled, you whip up a batch of icing and pipe on an intricate design. You lovingly set the cake on a beautiful stand—and then put the cake on a card table on the sidewalk and just walk away.

Sure, maybe a crowd of appreciative dessert enthusiasts will happen upon your cake. Or maybe your cake will fall victim to squirrels, weather, or simple obscurity.

"Sufficient funding for all stages of the research process, including communication, is crucial for the well-being of humans and our planet."

That metaphorical scenario is why my work as a science communicator matters. Defaulting to traditional academic communication strategies means that insights about important topics such as addiction, environmental toxins, and food insecurity can become buried in esoteric journals and conference proceedings. I help my clients get their research into the hands of people who can implement their results, such as policymakers and service providers. Together, we develop plain-language briefs, attractive infographics, and compelling presentations that reach beyond the scientific academy.

Unfortunately, when researchers face funding cuts, communication is the easiest part of the scientific process to eliminate. Scientists are funded to conduct research, so they plan studies, collect the data, and analyze results; however, they may not have room in their budget to support comprehensive, effective dissemination of their work.

When research doesn't reach the people who can apply it, the study is ultimately useless. Sufficient funding for all stages of the research process, including communication, is crucial for the well-being of humans and of our planet.

Lori Palen
Data Soapbox

To the Editors:
I have been a scientist for more than 50 years and have spent 46 of those years as a faculty member at City University of New York (CUNY). I taught

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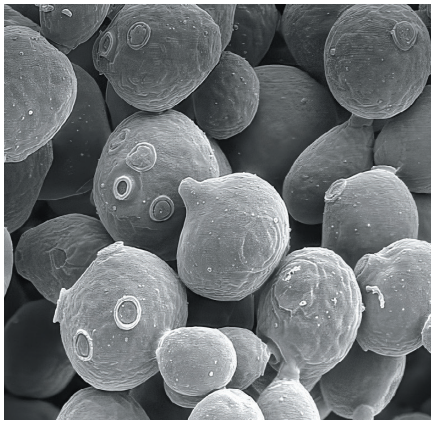
thousands of New Yorkers, both natives and immigrants; some of them are now famous and some are rich. I solicited and administered more than $30 million in federal grant money for labs at CUNY. Because of our diverse student body, much of our support came from diversity, equity, and inclusion programs.

About $5 million supported my research group, which focused on yeast cell walls and biofilm adhesins. Those subjects seem laughably academic and therefore a potential waste of the taxpayers' money. Nevertheless, we made discoveries that have led to commercial development and billions of dollars in corporate profits.

For example, our 1993 paper showed how yeast cells put antigens on their surfaces. In 1997, other scientists used that knowledge to invent a way to display any protein or antigen on a yeast cell. Molecular biologists and pharmaceutical companies use that technique for drug discovery hundreds of times each year to find treatments for cancer and other diseases (*as shown in this example below*).



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In 2012, a pharmaceutical start-up discovered a new drug class that would block that pathway and kill yeast. Today, one such drug is awaiting the results of phase 3 clinical trials. A chemical with the same effect is being tested to fight a fungal contamination that ruins crops and poisons food. These discoveries would not have been made without the insight of our diverse workforce as well as continued federal support. Our research has been an essential part of progress for the betterment of all of us.

Basic science is essential for us and for our children. Many of my parents' generation died from infections or from contaminated food. Penicillin injections and tetanus vaccines saved my own life several times when I was a kid. We are safer today because sustained research has led to new treatments for emerging and drug-resistant infectious agents.

Peter Lipke
Biology and Biochemistry (emeritus)
City University of New York

To the Editors:
Sex specific metabolites (SSMs) are endogenous compounds that create differences between the sexes, and SSM enzyme systems create a few but important sexual physiological divergencies. However, our metabolic knowledge is based almost exclusively on males due to an old assumption that male and female metabolites are all structurally identical and only vary in concentration, as with sex hormones.

"We are safer today because sustained research has led to new treatments for emerging and drug-resistant infectious agents."

SSMs are not well known, because, as the saying goes, "It's hard to find what you are not looking for." They are found in insects, blue crabs, and highly inbred mice. In these mice, SSMs constitute less than 10 percent of total metabolites.

A normal man is genetically 99.9 percent identical to other men, and the same is true for women to women; however, men's genes are only 98.5 percent identical to women. The sex difference is 15 times greater than the divergence within a sex, leaving sufficient genetic room for metabolic differences.

Women are afflicted with lupus at seven times the male rate, and men are six times as likely as women to have autism. Why do certain drugs work for only one sex? Are there few, but important differences in biochemical pathways?

Mass spectrometry is an excellent technique for finding SSMs in tissue extracts. The technique is extremely sensitive and can simultaneously detect thousands of metabolites. As sex patterns are recognized, sex–specific diagnoses can lead to personalized medicine.

Robert Kleps
Pharmacognosy
University of Illinois at Chicago

To the Editors:
I work on ready-to-use (RTU) injectable medications, which are revolutionizing contemporary healthcare by offering prefilled, premeasured pharmaceutical formulations that eliminate the need for on-site reconstitution or dilution. These formats, typically delivered in prefilled syringes, auto-injectors, or ready-to-administer intravenous bags, significantly streamline drug administration workflows and bolster both clinical and operational efficiency.

One of the most profound benefits of RTU injectables is the substantial reduction in medication errors. According to a 2014 study published in *Clinical Pharmacology: Advances and Applications*, medication errors represent 19 percent of all adverse events, account for up to 7,000 deaths annually, and occur more frequently in ICUs. RTU formats mitigate these risks by removing manual preparation steps such as drawing, measuring, and mixing, thereby minimizing the potential for incorrect dosing, microbial contamination, or particulate introduction.

In addition to improving patient safety, RTU injectables deliver significant efficiency gains across healthcare systems, which allows clinical staff to focus more on patient-centered care activities. From a patient perspective, RTU formats simplify at-home administration, leading to improved medication adherence and therapeutic outcomes.

Niravbhai Patel, PhD, FRSC
Nivagen Pharmaceuticals Inc.

How to Write to *American Scientist*

In addition to submissions regarding the "Science Is Important" call for letters, brief letters commenting on articles appearing in the magazine are also welcomed. The editors reserve the right to edit submissions for length and clarity. Please include an email address if possible. Address: Letters to the Editors, P.O. Box 13975, Research Triangle Park, NC 27709 or editors@amscionline.org.

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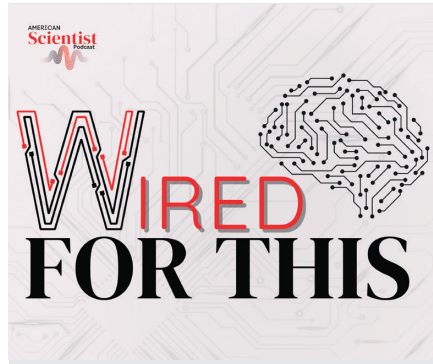

The *American Scientist Podcast* presents a new limited series, "Wired for This," which premiered on September 10 and will run for six episodes through the end of 2025. "Wired for This" offers an in-depth look at how we think, believe, change, and connect. In the first episode, host Celia Ford interviews social psychologist Paul O'Keefe, a professor of organizational behavior at the University of Exeter Business School, about his research on how a person's mindset can affect their success in school, careers, and beyond.

What does it take to change a mind? In episode two, we hear from Katy Milkman, a professor at the University of Pennsylvania Wharton School of Business and host of the behavioral economics podcast *Choiceology*. Milkman is the codirector of the Behavior Change for Good Initiative, a research center that conducts megastudies about how to promote lasting behavioral changes.

Episode three tackles difficult conversations with guests Emma Levine and Shereen Chaudhry, both of whom are professors of behavioral science at the University of Chicago Booth School of Business. Levine studies the psychology of altruism, trust, and ethical dilemmas. Her research investigates the tension between honesty and benevolence, examining how these dynamics influence interpersonal communication. Chaudhry teaches negotiations to business students and studies how people navigate social interactions and relationships. Her research reveals that everyday conversations often carry hidden negotiations over reputation, responsibility, and relationships.

Each episode of "Wired for This" will challenge your thinking and offer fresh perspectives on the world around us. Tune in to "Wired for This" every other Wednesday starting September 10 on Spotify (*QR code below*), Apple Podcasts, iHeartRadio, and more. Follow the *American Scientist Podcast* today to receive updates when new episodes are released. Episodes are also linked from the *American Scientist* website.

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The Stories Rivers Carry
Robert Macfarlane's newest book, *Is a River Alive?*, explores the literal and figurative intersections between these waterways and the larger ecosystem.
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The Complex Life of Frida Kahlo
A new animated film, *Hola Frida*, introduces children to the artist. Kahlo is perhaps best known for her self-portraits, many of which incorporate themes of anatomy, chronic pain, and disability, as well as nature and Mexican culture.
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Getting to the Heart with AI

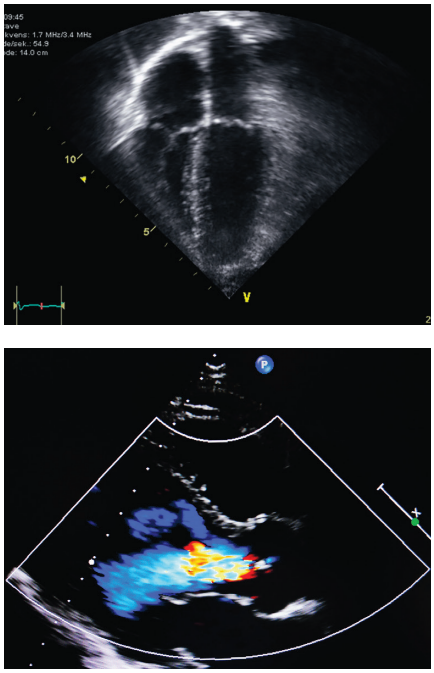
Deep learning programs may be able to examine data from a common medical test to flag patients with undiagnosed cardiac disease.

A patient with serious heart disease might go without noticeable symptoms for a long time. If, for instance, they have a heart valve that isn't opening or closing properly, they might start getting fluid buildup in their lungs that will only very gradually affect their breathing, among other problems. Frequently, these patients end up as severe cases before they even know they are developing heart disease. "All of us who work in medicine have seen too many cases to count of patients who have ignored their symptoms," says Timothy Poterucha, a cardiologist at the Mayo Clinic in Minnesota. "They just brushed off their shortness of breath, or they would go to sleep and hope their chest pain would go away." Now, Poterucha and his colleagues are researching how the data analysis abilities of certain types of artificial intelligence might help them use a common medical exam to get around this problem and diagnose more heart disease patients sooner. "You can only treat the patients you know about," Poterucha says.

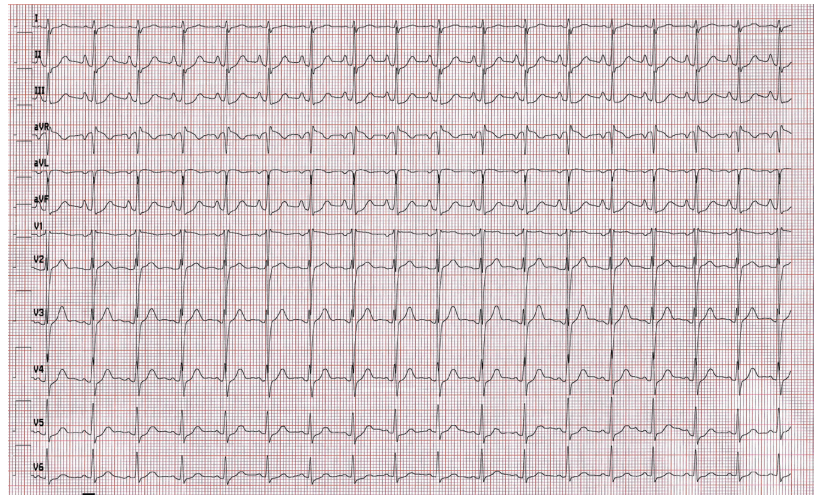
The team is currently working on a system for diagnosing *structural heart disease*, an umbrella term for any physical ailment related to the heart's valves, chambers, or muscles that makes the heart have to work harder to pump blood. "The heart has four valves, and their job is to control the flow of blood through the heart," Poterucha says. "If they become leaky or narrow over time, that can cause more and more strain on the heart. This strain starts off without patients feeling it, but as the disease gets more severe, the patients can get short of breath, they get heart failure, and they can die."

Diagnosing structural heart disease requires an echocardiogram—an ultrasound image of the heart and its blood flow. But that test is more expensive so fewer people receive it until they have developed more severe disease. A much more common test is the electrocardiogram (ECG)—the series of blips from heart electrical activity as it contracts, opens valves, and moves blood around. "There could be as many as several hundred million ECGs done in the world every year," Poterucha says. "They can be done anywhere with almost no training, and they are inexpensive as far as medical tests go, so that gives it an enormous advantage." Poterucha and his colleagues had already been working with AI deep learning models for other types of heart disease, so they wanted to see if they could train an AI neural network to take data from ECGs and predict which patients might be at high risk for structural heart disease and therefore should be recommended for an echocardiogram.

As the team recently reported in *Nature*, they were able to collect patient tests from an eight-hospital system in New York City, taken over a span of 15 years. They used only records of patients who'd had an echocardiogram taken within a year after an ECG. This criteria gave them a set of almost 800,000 records to train their model, a further set of about 35,000 records to validate the AI's training, and then a set of almost 45,000 patient records for testing the model. The model was trained on a number of traits in echocardiograms that can indicate structural heart disease, including the heart's pumping



An echocardiogram uses ultrasound to create an image of the inner workings of the heart (*left, top*). This imaging is usually required to diagnose structural heart disease, such as a view that shows a heart with aortic valve regurgitation, in which blood is leaking through a faulty valve (*left, bottom*). Structural heart disease usually cannot be diagnosed with an electrocardiogram (ECG), which shows the heart's electrical activity as it beats (*below*). However, researchers are developing a new AI system that can use the more common and less expensive test for this purpose.



Kjetil Lenes, Oslo, Norway/Wikimedia Commons; Korawig Boonsua/Alamy Images; Blackeyelion/Wikimedia Commons

function, the thickness of the heart's walls, the presence of high pressure within the heart, and evidence that the heart valves have disease. The model was then trained on each patient's associated ECGs; the researchers directed the AI to look at the amplitude, duration, and interval of different segments of the waves, and to extract traits that the AI learned could indicate the presence of structural heart disease. After working through the training and validation sets, the model, called EchoNext, was able to identify patients in the test set who were at high risk for structural heart disease with an accuracy of 77 percent, using only ECGs. A subsequent test on data from other hospital systems produced similar results.

To further validate the model, the team created a subset of 150 ECGs and asked a group of cardiologists to diagnose them for structural heart disease. The cardiologists' accuracy was 64 percent, and 69 percent when they were also given the AI score. "There are some signals we can look at as cardiologists that can indicate if a particular ECG is likely to be from a patient with structural heart disease," Poterucha says. "But it's kind of a challenging task that we don't train ourselves exactly for." Poterucha also notes that, in practice, a doctor will have far more information with which to make a diagnosis. "When I see a patient, I am able to take their history, find out their symptoms, look at their past medical records and prior testing, do a physical exam and listen for murmurs or find signs of heart failure with swelling in their legs, fluid in their lungs—and then I look at their ECG," he says. "The actual clinical implementation will be a cardiologist with lots of information who has the assistance of an AI model."

Poterucha hopes that these systems will help catch patients who do not have a lot of follow-up care, and will help decrease the amount of time doctors need to make a diagnosis or recommend further testing. The system is currently undergoing clinical trials in a series of urban emergency rooms, in which patients are often not well connected to routine medical care. "Our goal is to try to look at every single ECG done in every single patient in all the hospitals that this study is being conducted at, and find those patients who are mostly likely to have undiagnosed structural heart disease, and then we can go on and test them, find the disease, and then do something about it," Poterucha says. "We need to set up our health care system in such a way that we try to improve care overall for everyone, with a particular focus on the patients who get the least medical care."

The term *AI* can have mixed connotations for many people, but so far, Poterucha says that patient response to the technology has been positive. In a separate, previous trial, Poterucha and his colleagues used AI to identify a different form of heart disease. They would cold-call patients, which Poterucha admits could be disconcerting, but he says most patients were appreciative. "It's an unusual call for a patient to get, when we call them and say, 'Hi, we've built an AI system that analyzed your ECG and your echocardiogram, and we think you might be at risk of having this particular health condition; would be interested in coming in for testing?' But we found that patients tend to be grateful that someone thought it was worthwhile to go the extra mile to build a system to detect the disease, and they're glad that we can do something about it."

Patients will not be visiting AI doctors anytime soon, but Poterucha and his team think that these tools will help busy medical systems better handle large amounts of data and high patient loads, and be more proactive in diagnosing patients earlier, when they can be more effectively treated. As Poterucha notes: "We can use the ability of humans to take a very comprehensive history and look at a lot of data, and focused AI models which are very good for one particular task, and we can pick out a way to combine those strengths into doing the best possible job we can to detect heart disease." —*Akilah Abdulraheem*

Guideposts for Regeneration

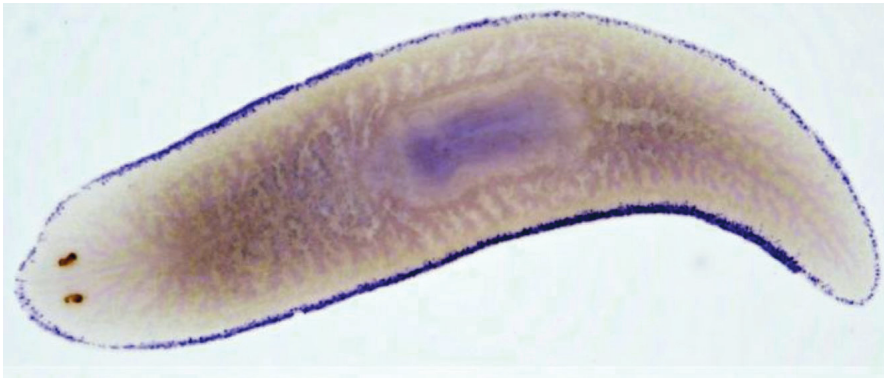
Specialized flatworm cells turn on position genes to direct when and where repairs happen after an injury.

The waves crash on the shore, turning the sand a dark brown. A massive, serpentlike beast looms over Hercules, its multiple heads thrashing and ready to strike. Hercules swings his sword, slicing through the beast and watching as one of its heads falls to the ground. He steps back, preparing to strike once more. But his success is short-lived: From the wound, two new heads emerge, each one angrier than the last.

The regenerative powers of the Hydra have been a mythical symbol of resilience for centuries. But the ability to grow back severed body parts exists across countless species, some with a capacity bordering on the unbelievable. Salamanders, for instance, are capable of regrowing limbs in mere weeks, and zebrafish can repair damaged hearts. Even humans possess limited regenerative abilities: The liver can heal large portions of itself after a severe injury. But no animal embodies the marvel of regeneration quite like the flatworm.

Flatworms encompass a wide array of species, but one especially intriguing group is the planarians. These worms are found in various habitats, largely in freshwater and saltwater, but some have also adapted to land. They also range widely in size: *Bipalium kewense*, a terrestrial planarian from South America, can reach up to 25 centimeters in length, whereas others measure just a few millimeters—barely longer than a fingernail. But all planarians share a powerful ability: Cut one into pieces, and within a week, each fragment will regenerate into a fully formed, genetically identical clone of the original.

This ability is enabled by a special type of stem cell called a *neoblast*, which makes up about 20 percent of all the cells in the worm's body and is its only dividing cell type. These cells can transform into any of the worm's more than 120 different cell types, in-



Salah Ayoub, BIMSB/MDC and Jordi Solana, BIMSB/MDC/Oxford Brookes University

The diminutive planarian *Schmidtea mediterranea* can range from 0.1 to 2 centimeters in length, but it is a giant in its ability to regenerate. The one shown here, with its characteristic cartoonlike eyespots, has been stained to show the presence of messenger RNA.

cluding more neoblasts—an ability that's called *pluripotency*—which allows them to rebuild missing tissues.

The remarkable regenerative abilities of planarians have fascinated scientists for more than a century. In the late 1800s, American evolutionary biologist Thomas Hunt Morgan documented how fragments could regenerate into complete worms. And before Morgan, Charles Darwin collected planarians during his travels, marveling at their adaptations and striking color patterns.

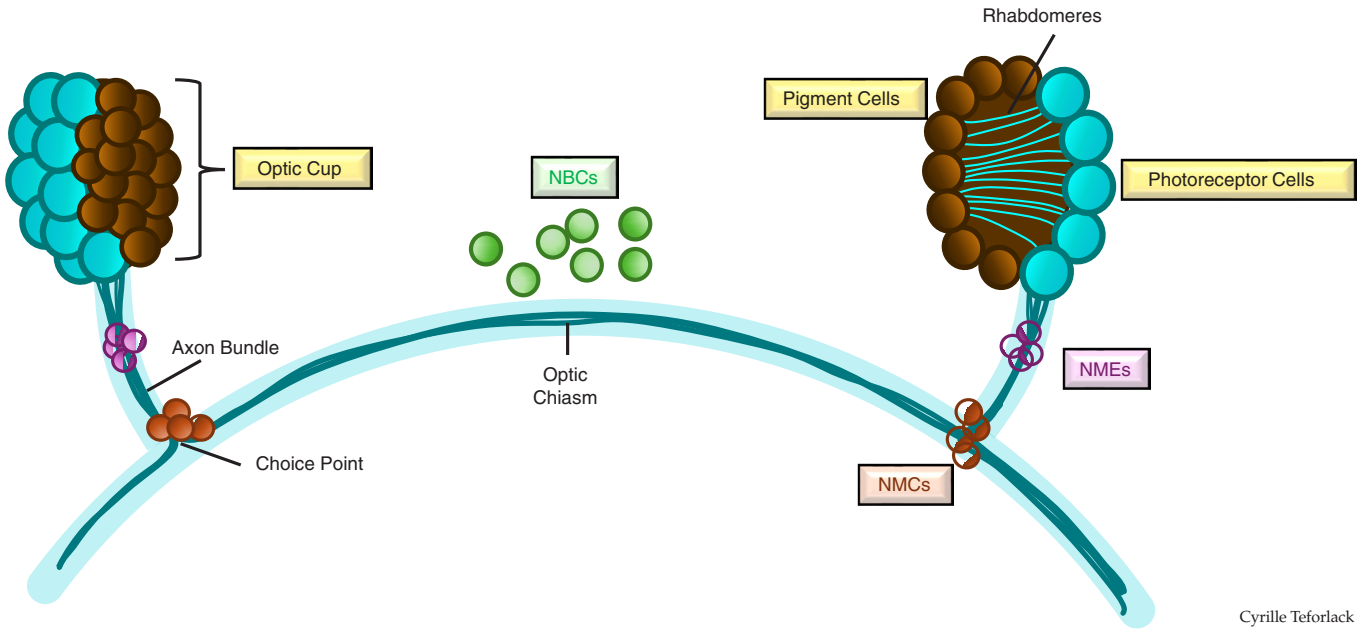
Despite this extensive study, key questions remain: How do neoblasts determine the types of cells they will become? How do they tell their location in the body and navigate to where they're needed? Interested in uncovering the answers to these and many other questions, biologist Peter Reddien of the Massachusetts Institute of Technology and his team began looking at one freshwater planarian species, *Schmidtea mediterranea*, which is characterized by cartoonlike eyespots at the top of the anterior tip of its body. "There are a lot of good organisms for studying regeneration," Reddien says. "But planarians are some of the world's best regenerative organisms, and they have tissues similar to those found across bilaterally symmetrical animals, from musculature to nervous system, skin, intestine, and other tissue types. So they are a good model for studying the regeneration of widely seen cell types in animals."

To understand how cells recreate specific missing tissues, Reddien and his team started with one of the simplest organs in the planarian body, the eyes. Planarian eyes are composed of just two main cell types: pigment cells, which cluster together to form a light-focusing structure called an *optic cup*, and photoreceptor cells, which detect light and guide the worm's movement. Each photoreceptor cell extends specialized projections called *rhabdomeres* into the optic cups, akin to rods and cones in the human eye. Their nerve fibers, or *axons*, must navigate precise pathways within the worm's body: Some extend down and back to connect with the brain, whereas others project contralaterally, reaching toward the opposite eye and splitting off at a region called the *choice point*. This wiring enables the worm to integrate light signals from both eyes and navigate its environment. Through a behavior known as *phototaxis*, planarians move away from light toward shaded areas, avoiding open water where they are vulnerable to predators.

These small organs contain complex neuronal connections and trajectories that must be precisely assembled both during their initial formation and after injury. During development, many animals have cells that serve as "guideposts" to direct pioneering neurons toward their targets. Then, once their connections are made and other axons follow the existing tracts, the guidepost cells become dispensable and are lost. Therefore, in the adult animal, if the system is damaged, there are no guidepost cells present to steer regenerating axons to the correct locations. Reddien began to speculate about what might allow regeneration to occur so readily in the planarian visual system. "Guidepost cells are like the scaffolding around a building," he explains. "But if you injure the system, what are you going to do if the scaffolding is not there anymore? What we began to wonder is: What if part of the solution is the retention of guidepost cells into the adult stage, such that the scaffolding would still be there? Then, the guideposts could still instruct the regeneration of the nervous system. That's what we began to investigate."

Reddien and his team suspected that specialized cells retained near the planarian eye might serve as these guideposts, steering regenerating photoreceptor axons toward their targets. To find these cells, they turned to a method called *fluorescence in-situ hybridization* (*FISH*), which uses glowing probes made from synthesized messenger RNA (mRNA) to latch onto specific genetic sequences in the worm's body. When hit with a focused laser under a microscope, the probe lights up, allowing researchers to visualize specific cells based on the mRNA they express. This technique provided the Reddien lab members with their first observation of a few small cells near planarian eyes. "A staff scientist in the lab, Lucila Scimone, noticed a tiny number of muscle cells right next to the eyes of planarians, and that was curious: They're not part of the eye, seemingly, and there's just one or two right next to both eyes," Reddien explains. "We had our suspicions that they would be performing some kind of regulatory function, because we found in prior work that the muscle in planarians is the source of instructions guiding processes of regeneration."

The team found that the tiny cell clusters expressed two genes, called *notum* and *frizzled 5/8-4*, which are known for their role in establishing body position—information that is a hallmark of development and regeneration in all animals. During development, cells throughout the body express such *position control genes* (PCGs) in patterns that inform the surrounding cells about their location and the type of cell they should become. These genes are also important after injury in planarians. For example, *notum* expression has been shown to stimulate head regeneration in wounds that are anterior-facing. Another gene, called *smedbmp4-1*, is required for correct regeneration at the body's midline and for maintaining the back-belly axis of the animal. When cells expressing these PCGs are lost, remaining cells change their gene expression to restore such positional identities, ultimately guiding correct anatomical position during regeneration. Highly regenerative vertebrates such as axolotls that can regrow appendages after injury will typically express PCGs in cells of the connective tissues of the limb. Similarly, Reddien's lab found that, in



Cyrille Teforlack

The planarian optical system consists of pigment cells that form an *optic cup*, into which photoreceptor cells extend *rhabdomeres*, akin to rods and cones in the human eye. Axon fibers extend from the photoreceptors and branch at the *choice point*, where they either connect to the brain or cross over to the opposite eye. In doing so, they pass through the *optic chiasm*, a midline structure where fibers from both eyes intersect. If there is damage to the visual system, a gene called *notum* that guides regeneration is expressed in muscle cells near the eyes (NMEs) and at the choice points (NMCs), and in brain cells where axons cross between brain hemispheres (NBCs).

worms, PCG expression took place in muscle cells throughout the body, with a tiny subset that seemed to be localized to the eye. "We found this system of positional information in planarians was harbored in the musculature and functions as its connective tissue, an intriguing connection between regeneration in vertebrates and planarians," Reddien says. "The whole blueprint for the locations of where things should be in the animal is determined by gene expression patterns in the muscle. It's incredibly beautiful."

These guidepost muscle cells appeared in three distinct locations in the visual system: near the eyes (called NMEs, for *notum*-expressing muscle cells near the eye), at the two choice points (called NMCs, for *notum*-expressing muscle cells at the choice points), and at the midline where axons cross between brain hemispheres (called NBCs, for *notum*-expressing brain cells). "When Lucila showed me pictures of these cells, we easily could have moved on and not studied them, because we didn't have the idea of what they did at the beginning," Reddien recounts. "But they were so odd that we couldn't help but think, 'There's got to be something here; maybe we should look into these!'"

To test the role of guidepost cells in regeneration, the team surgically removed a single eye and its associated axons up to the choice points, and then observed what happened. Within days, new axons sprouted from the regenerating eye and reached toward the existing uninjured eye. Taking a deeper look, the researchers also noticed that the trajectories of the regenerating axons seemed to align with the position of the different guidepost cell populations of the uninjured circuitry—suggesting these cells were acting as a signal to turn the axons in the correct direction, similar to their function in other parts of the body to maintain the worm's anatomy. "One of the key things that we noticed was that there was a little variability in the exact position of the guidepost cells, and there was a little variability in the exact position of the axons," Reddien explains. "We'd even occasionally see a stray axon—when we looked at the axons and the guidepost cells together, wherever the guidepost cell was, even if it was a little out of position, that's where the axons were."

Then came a bigger test: What happens when the entire visual system is destroyed? The team decapitated the worms, forcing them to rebuild both eyes and brain. Remarkably, the process unfolded like clockwork. One day after amputation, eye cells began to form. The next day, axons emerged and bundled near the newly formed NMEs that help to organize their path. By day three, NBCs appeared at the midline, guiding axons from both eyes toward one another before they projected into the regenerating brain. These guidepost cells, the researchers think, function like a tracking system—helping the regenerating axons navigate the complex terrain to reconnect the visual circuit. As the team recently reported in the journal *PLOS Genetics*, they have also found that photoreceptor neurons interact with the brain's glial cells to support their regeneration.

The mythical Hydra's ability to regrow two heads for every one lost is a thing of fantasy, but the planarian's story is real and unfolding under the microscope. Although flatworms may seem like obscure lab animals, understanding how they rebuild entire organs could one day help us coax human stem cells to regrow tissues lost to injury or disease. Reddien thinks that learning about how guidepost cells function in nervous system regeneration may have applications in human regenerative medicine. "A lot of the molecules we've found are conserved in humans," he says. "As we're finding mechanistic concepts of regeneration like the importance of a guidepost cell for neural wiring, one can think about engineering applications with this type of knowledge." —*Cyrille Teforlack*

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Inspired by Immunity

La Jolla Institute for Immunology

The human immune system is a marvel of complexity, coordinating the activities of many different cell types to try to protect the body from invaders. There are cases when it might overlook hostile forces, such as cells that have become cancerous, or when it overzealously attacks tissues that it should recognize as belonging to the body, as happens in diseases that range from rheumatoid arthritis to diabetes to Parkinson's. Alessandro Sette, Head of the Division of Vaccine Discovery and the Center for Infectious Disease and Vaccine Research at La Jolla Institute for Immunology in California, has spent decades unraveling the immune system's functions and uncovering ways to harness it for better disease prevention and treatment. One of his focuses has been on epitopes, *the specific fragments and structures that the immune system recognizes. He has overseen the design and curation efforts of the national Immune Epitope Database (IEDB). Sette is the recipient of Sigma Xi's 2025 William Procter Prize for Scientific Achievement. He spoke with editor-in-chief Fenella Saunders about his work. (This interview has been edited for length and clarity.)*

How did you get interested in studying immunology?

I really fell in love with the study of the immune system for a couple of different reasons. In my university studies in math and chemistry, I was very reductionistic, I wanted to go down to the molecule. And immunology was, of all the biological sciences, one of the disciplines that was really starting to describe events in biochemical terms. You could measure very accurately antibody-antigen interactions. We were starting to understand the genes linked to antibody rearrangement, and also the whole mystery at that time of what T cells recognize and how they recognize it. The other big thing is that it had real potential for applied science. I'd always been very interested in pursuing avenues with my research that could have an impact, and immunology was a science that was clearly very close to human health.

How has the study of immunology advanced since the start of your career?

Things have changed so much that it's hard for someone today to appreciate. Back when I was starting, to sequence a gene or synthesize a peptide was a big deal. Forget about having genomes. I would literally synthesize peptides by hand, one residue at a time, come back in two hours, add another residue, and in a few weeks you'd have a peptide. Just the amount of data that can be generated, the amount of granularity, has increased by orders of magnitude.

Can you explain how different parts of the immune system interact?

The immune system is made of different components that work together in a synergistic way, but they are very different in the ways they recognize a substance, an antigen. Antibodies recognize proteins on the outside of a virus or a bacteria, and they bind to it to neutralize its activity, so they are great at preventing infections.

But what if the microbe makes its way inside our cell? Then it becomes invisible to antibodies. That's where the T cells come in, because they have an uncanny capacity to recognize fragments, or *epitopes*, of a virus or a bacteria. What happens is that when a virus or a bacteria gets inside the cell, it gets broken down into pieces. These pieces end up being bound to certain proteins called HLA [human leukocyte antigen] molecules. These proteins, with a fragment bound to them, end up on the surface of a cell, and that's how a T cell can tell that that particular cell is infected. The T-cells kill the infected cell and secrete other proteins called *cytokines* that amplify and potentiate the immune response to favor the production of antibodies.

T cells are not particularly good at preventing an infection, but they are what is required to terminate an infection and prevent disease. Antibodies are great to prevent an infection. So that's why they work together.

How are antibodies generated?

The antibodies are made by B cells, but B cells become activated if the antibodies that they express on their cell surface bind the protein or the surface of the virus. Then that particular B cell that bound the target starts to proliferate, rearrange its genes, secrete antibodies, and mount an immune response.

How can you develop therapies inspired by immune responses?

In whatever disease we are interested in, we start from the organism. It may be someone who has been unlucky enough to get the flu. But then we zoom in and say, okay, something is going on in the lung. In the lung, which cells of immune systems are at play? Which cell is infected? Which cell is responding? What is being recognized as a virus, and of that virus, which particular protein? And of that particular protein, which specific fragment? So we go all the way down to a fragment of a protein with a sequence of a few amino acids. Once we have that, then the journey starts in reverse. Now we can use this fragment as bait, to fish out the different cells that are recognizing it. And then we ask: What do they do? What kind of activation? Are they exhausted? Are they proliferating? Are they secreting one particular mediator or another?

We are interested in a whole series of diseases from viruses and bacteria. Those are instances in which you benefit, most of the time, from the immune response. Those responses are amplified by vaccines. Another instance in which you benefit from immune response is when you react against a cancer.

There are other instances in which the immune response is not so welcome. One example is allergies, where you violently react to smelling a flower and inhaling that pollen, and it's really no harm to you. Other instances of an unwelcome immune response are diabetes or rheumatoid arthritis, where your body somehow has an immune response directed against components of your own body. An area where we are working a lot these days is neurodegenerative diseases, such as Parkinson's, Alzheimer's, and ALS [amyotrophic lateral sclerosis]. Again, you have an inflammatory phenomenon that can maybe trigger the disease.

In all these different cases what we try to do is to use the fragment to ask questions. What's the difference between good and bad outcomes? Why is that person reacting that way and not in another way? You would like to induce the type of immune response that is associated with smelling flowers all day, as opposed to having an asthma attack and ending up in the emergency room.

How can this research help to stop an overactive inflammatory response?

For neurdegenerative diseases such as Parkinson's and Alzheimer's, the disease takes a long time to take hold. The clinical effect of Parkinson's, the shaking and the impairment of cognitive function, is a result of a certain area of the brain called *substantia nigra*, which makes dopamine, having been destroyed. But that process takes decades. It's very similar to what happens in diabetes: Unwanted activity of T cells gradually destroys the cells in the pancreas that make insulin. If we could recognize this process, then that inflammation, that immune response, could be shut down.

There's some interesting data on people who have Crohn's disease or irritable bowel disease and are treated with monoclonal antibodies that essentially shut down a certain inflammation mediator. These medications have been used in thousands of people over the course of decades. People who get this treatment when they're younger don't get Parkinson's. That means that if you can shut down this inflammation, you can stop Parkinson's in its tracks. Now, that doesn't mean you're going to put everybody that turns 50 on these medications: they have side effects, and it's expensive. But if you had a test to recognize people that are at risk, that would be a call to arms to intervene.

What are the prospects for applying your results to personalized medicine?

The process of cancer epitope identification can be very personalized. Your normal cells accumulate mutations, and those mutated fragments are not normal parts of your body, so they are potential candidates for your immune system to recognize. The particular HLA molecules that present this fragment to the immune response are different from one individual to the next. And particular mutations most often are different from one cancer to the next in one individual. So that's why people are interested in making personalized cancer vaccines or targeted immunotherapy.

On the opposite end of the spectrum, if I want to develop a reagent to monitor the type, the magnitude, or the quality of immune response induced by a vaccine, it's not convenient to try to identify the specific epitope on an individual basis, because what you want is something that works in the population that has been immunized with a vaccine. The other complication is that these HLA molecules can be different in different ethnic groups. The U.S. population is very ethnically diverse, so you want to make sure that your reagents will work in all the different ethnic groups that are represented in the population.

"You would like to induce the type of immune response that is associated with smelling flowers all day, as opposed to an asthma attack."

The other issue is the issue of conservation across relative species. And that actually is also an important consideration that can drive the immune response. One of the first times that was clearly apparent to us was when we were studying allergic reaction to pollens. Obviously there's a lot of plants and a lot of different types of pollens, but many plants are related to one another. If someone is allergic to grass, there's a lot of different types of grass. What happens is, a person is breathing ragweed or timothy grass or another grass, and it happens that certain fragments are going to be shared, or be very similar, between timothy grass and other grasses. If you have an immune response that generically sees timothy grass, but then you breathe another grass, your immune system will get a boost for both fragments that are shared between the two different types of grass. Over time your T cell response will be skewed in recognizing things that are similar or shared in different grasses. The same thing happens for bacteria and viruses. To a certain extent, this reaction also generates some kind of a background, preexisting immune reactivity that is often, in the context of infectious diseases, helpful. In the case of SARS-CoV-2, there's a lot of data that showed that people who had been recently exposed to other coronaviruses had less severe disease manifestation. This effect is particularly important when there is an infectious agent that is completely new. That, for example, is widely believed to have been the case in the 1918 flu pandemic. This flu was something totally new that the human population had no pre-existing immunity against, and that's one of the reasons why it was as damaging as it was.

What has the role of databases been in advancing this research?

We have been running the Immune Epitope Database (IEDB) since 2003. We also have launched a sister database called CDER, and that is specifically hosting all data related to cancer epitopes published in the scientific literature.

This freely available resource catalogs all known immune responses against viruses, bacteria, antigens, allergens, everything. That has been a passion of mine and my colleagues, making this data freely available. If it's published in the scientific literature, we extract that data and we curate it. The key, very powerful thing is that the data is put in a context that is computer-readable. That way you can collate a thousand different studies and look for trends.

You can ask, is there a general rule that a certain position in this fragment is more immunogenic than another one, or are there particular regions of a protein that are more prone to have mutations that are recognized by the immune system? You can do a lot more, if you can collate data from tens of different independent studies. That also gives you more confidence that that result is reliable. ■

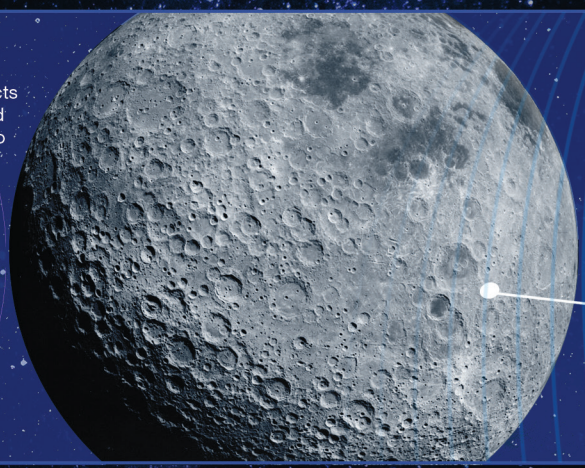
Infographic | Gary Schroeder

LuSEE-Night | A Lunar Farside Radio Telescope

Cosmologists are seeking the *Dark Ages signal*, radio waves emitted by hydrogen atoms during the mysterious era after the Big Bang but before the first stars lit up. Detecting the Dark Ages signal could help answer some of the biggest questions in cosmology, such as the nature of dark energy and the origin of the large-scale structure. LuSEE-Night (the Lunar Surface Electromagnetics Experiment-Night) is a pathfinder radio telescope that will operate on the farside of the Moon—studying the universe from a previously inaccessible location, at a frequency range that has never before been observable.

Drowning in Noise

Radio waves from the Dark Ages cannot be measured from Earth because the atmosphere absorbs and reflects them before they reach the ground. Such signals would also be drowned out by noise from our ubiquitous radio communications and other electronics.



Finding a Quiet Sky

On the lunar farside, LuSEE-Night will use the Moon as a shield to block radio interference from Earth. Hydrogen emission has a natural frequency of 1.42 gigahertz. Due to the expansion of the universe, the Dark Ages signal will show up at a much lower band, between 0.1 and 50 megahertz.

redshifted 21-centimeters signal

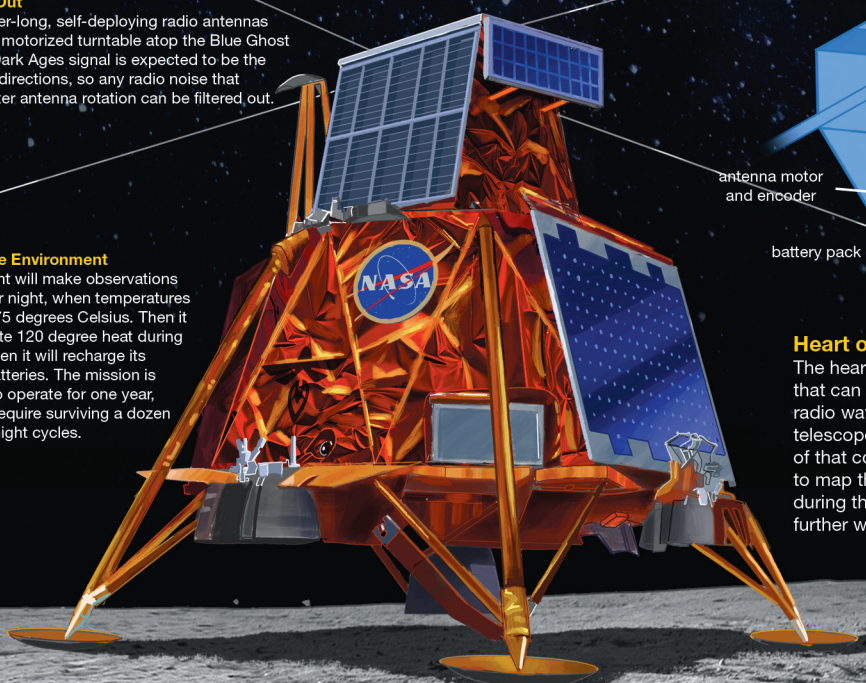
Landing Target
28.8 degrees south, 182.2 degrees east

A relatively high-altitude location on the Moon's southern hemisphere provides a good view of the radio sky, along with favorable access to an orbiting relay satellite.

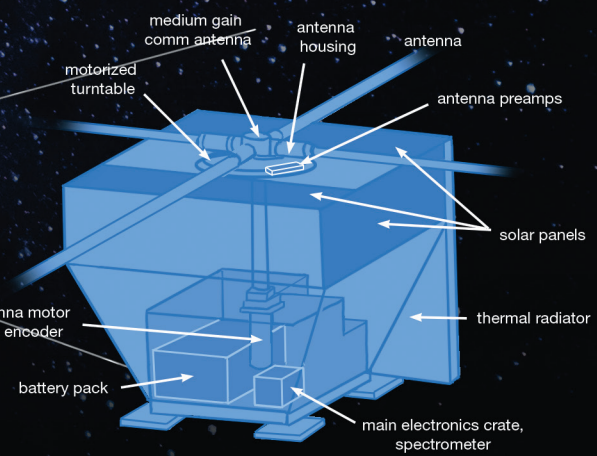
Radio Silence

A commercial Blue Ghost lander operated by Firefly Aerospace is scheduled to deliver LuSEE-Night to the surface of the Moon next year. Because a radio-quiet environment is crucial, all other parts of the lander will shut down at the end of the first lunar day, and LuSEE-Night's electronics will be fully shielded.

Antennas Out
Four 3-meter-long, self-deploying radio antennas rotate via a motorized turntable atop the Blue Ghost craft. The Dark Ages signal is expected to be the same in all directions, so any radio noise that changes after antenna rotation can be filtered out.



An Extreme Environment
LuSEE-Night will make observations during lunar night, when temperatures drop to –175 degrees Celsius. Then it must tolerate 120 degree heat during the day, when it will recharge its onboard batteries. The mission is designed to operate for one year, which will require surviving a dozen lunar day–night cycles.



Heart of the Experiment

The heart of LuSEE-Night is its radio spectrometer, a device that can simultaneously tune in to multiple frequencies of radio waves, from 0.1 to 50 megahertz, collected by the telescope's antennas. Measuring the frequency and intensity of that cosmic radio emission will eventually allow researchers to map the temperature and distribution of hydrogen gas during the Dark Ages. The lower the detected frequency, the further we are seeing back in time toward the Big Bang.

In this roundup, associate editor Nicholas Gerbis summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/

One Queen, Two Species

Messor ibericus ant queens can clone males of another species (*M. structor*) as a colony survival strategy. This necessity, called *xenoparity*, marks the first known nonparasitic instance of one species' eggs spreading another species' genome (male hermaphrodite conifers and clams, for example, clone themselves by hijacking other species' eggs). Typically, ant males come from unfertilized eggs that contain only the queen's chromosomes. When a male mates with his queen, she stores his sperm and later fertilizes her eggs with it to produce female workers and, rarely, queens. But a team led by scientists at Montpellier Institute of Evolutionary Sciences in France believes a past genetic change has caused fertilized *M. ibericus* eggs to produce only queens, unbalancing the colony. To cope, the queens began mating with, then cloning, *M. structor* males. Now, by removing her own maternal genome from her eggs and replacing it with genetic material from an *M. structor* male, she can produce a male with solely *M. structor* genes. Eggs fertilized by that male's sperm can produce needed female workers. Developing a way to clone the needed males in-house freed the *M. ibericus* from having to dwell near *M. structor* colonies.

From Juvé et al. 2025

Juvé, Y., et al. 2025. One mother for two species via obligate cross-species cloning in ants. Nature. *Published online doi:10.1038/s41586-025-09425-w.*

Dino Tooth as Climate Proxy

Scientists can now reconstruct atmospheric carbon dioxide levels from the Mesozoic Era using fossil dinosaur teeth. This approach makes ecological and atmospheric inferences by comparing the ratios of three oxygen isotopes: ^{16}O, ^{17}O, and ^{18}O. Remarkably, the team led by researchers at Georg August University of Göttingen, Germany, has shown that triple-O isotope signals can persist stably in fossil teeth for hundreds of millions of years and can provide an animal-based proxy for climate in deep time. This finding matters because scientists cannot directly measure CO_2 except via ice cores, which at best go back only hundreds of thousands of years, so they must rely on proxies such as carbon isotopes in organic matter, boron isotopes in marine fossils, or the compositions of ancient leaves and soils. The triple-O method adds another arrow to that quiver, potentially improving validity and narrowing estimate ranges. The technique works because the atmospheric concentration of ^{17}O relative to ^{16}O and ^{18}O varies depending on atmospheric CO_2 concentrations and plant activity in the biosphere, which affect the ^{17}O anomaly oppositely. After animals breathe in atmospheric oxygen with this telltale ^{17}O ratio, hard tissues such as tooth enamel preserve it.

Feng, D., T. Tütken, E. M. Griebeler, D. Herwartz, and A. Pack. 2025. Mesozoic atmospheric CO_2 concentrations reconstructed from dinosaur tooth enamel. PNAS *122:e2504324122.*

Carbene Controversy Settled

In a first, researchers have confirmed that highly reactive carbon atoms called *carbenes* can exist in water, overturning more than half a century of controversy and confirming the 1958 hypothesis of Columbia University chemist Ronald Breslow. Intriguingly, the results suggest that, under the right conditions, cellular enzymes can protect carbene molecules and let them participate in biocatalysis, which is essential to life. Simple carbenes are structurally highly unstable and occur only as transient intermediates in chemical reactions. This instability is especially pronounced in water, which led many to argue previously that carbenes were incompatible with H_2O. Breslow proposed that the coenzyme thiamine (vitamin B_1) could provide transient carbenes that support catalytic activity by enzymes, even in a cell's aqueous environment, by ensconcing the carbene within a protective, positively charged ring of carbon, nitrogen, and sulfur. A team led by scientists from University of California, Riverside, has now proven him right: The ring stabilizes the carbene just long enough for it to participate in useful reactions. The group has used a similar strategy to design next-generation batteries and new cancer therapies.

Raviprolu, V. T., et al. 2025. Confirmation of Breslow's hypothesis: A carbene stable in liquid water. Science Advances *11:eadr9681.*

Island Syndrome Outfoxed

The brains of most foxes occupying California's Channel Islands (*Urocyon littoralis*) are not relatively smaller than the brains of their larger mainland relatives, the gray fox (*U. cinereoargenteus*); indeed, many are larger. This finding adds nuance to a mainstay evolutionary concept called "island syndrome," which predicts that trait shifts such as smaller, less energy-consuming brains will be selected for once animals become isolated on islands. These changes (which can include size shifts, greater tameness, and fewer offspring) largely stem from reduced food sources, predation, and selective pressures. When researchers from the University of Southern California and the Natural History Museum of Los Angeles County looked at island foxes on the six Channel Islands they inhabit, they found that this expected reduction in *encephalization quotient* (the size of an animal's brain relative to what would typically be expected given its size) occurred only in foxes on the second smallest, most isolated island. Indeed, some foxes developed more pronounced ridges and folds in their brains to compensate for reductions in cranium size over evolutionary time. The scientists suspect that larger brains are worth their higher energy requirements because they likely provide greater spatial cognition, cognitive processing, and problem-solving. These capabilities are especially valuable for the *Urocyon* that dwell on the four islands with complex woodlands, where the foxes need greater spatial abilities to hunt and forage in trees.

Wikimedia Commons

*Schoenberger, K. A., X. Wang, and S. Edmands. 2025. Increased brain size of the dwarf Channel Island fox (*Urocyon littoralis*) challenges "Island Syndrome" and suggests little evidence of domestication.* PLOS One *20:e0328893.*

Teams of Rivals

Adversarial collaborations offer a rigorous way to resolve opposing scientific findings, inform key sociopolitical issues, and help repair trust in science.

Stephen J. Ceci, Cory J. Clark, Lee Jussim, and Wendy M. Williams

In a personal history published in *American Psychologist* in 2003, economics Nobel laureate Daniel Kahneman lamented the needless acrimony and counterproductivity of scientific disagreements hashed out without structure or standards.

"I am convinced that the time I spent on a few occasions in reply–rejoinder exercises would have been better spent doing something else," he wrote. "Both as a participant and as a reader, I have been appalled by the absurdly competitive and adversarial nature of these exchanges, in which hardly anyone ever admits an error or acknowledges learning anything from the other. Doing angry science is a demeaning experience—I have always felt diminished by the sense of losing my objectivity when in point-scoring mode."

Kahneman advocated for a better way: adversarial collaborations—structured efforts in which scientists who disagree on a theory, finding, or interpretation work together to resolve their disagreements. "My hope is that . . . adversarial collaboration may eventually become standard. This is not a mere fantasy: It would be easy for journal editors to require critics of the published work of others—and the targets of such critiques—to make a good-faith effort to explore differences constructively. I believe that the establishment of such procedures would contribute to an enterprise that more closely approximates the ideal of science as a cumulative social product."

Traditionally, disagreeing scholars run independent research programs, writing papers, critiques, and rejoinders back and forth, aiming to persuade the scientific community that their side is correct. The process is often open-ended and inconclusive. We believe that adversarial collaborations, if widely adopted, could lead to more productive outcomes.

Neutral Ground

As in any effective debate, successful adversarial collaborations require setting clear ground rules. Scholars must agree on which positions to argue and on the values, criteria, and evidence by which they will judge which position "wins." They must agree that confirmation of their opponents' hypothesis casts doubt on their own and mutually publish the results. Some adversarial collaborations comprise only the sparring sides, whereas others use a neutral referee agreed upon by the adversaries or appointed by an outside body such as a journal's editorial board.

One successful example of such a collaboration, reported in 2023 in *Proceedings of the National Academy of Sciences of the U.S.A.* (*PNAS*), concerned the relationship between wealth and happiness. In it, Matthew A. Killingsworth of the University of Pennsylvania and Kahneman, a professor at Princeton University, resolved much of their long-standing debate over a possible income threshold governing the relationship between wealth and emotional well-being. Barbara Mellers, also of the University of Pennsylvania, served as a neutral referee, contributing to the adversarial collaboration design and to cowriting the resulting paper.

In 2010, Kahneman had reported in a *PNAS* paper that happiness increased with certain income levels, but that the relationship plateaued among incomes somewhere between $60,000 and $90,000. Conversely, in a 2021 paper, also in *PNAS*, Killingsworth had found a consistent and unabated rise in happiness as wealth increased. Their adversarial collaboration confirmed Kahneman's flattening pattern but found that it affected only the least happy 20 percent of the population. As it turned out, the disagreement arose from the authors' use of certain standard practices and data analysis assumptions. Thus, the collaboration not only addressed the key disagreement, it also amplified a methodological caveat: Although certain statistical practices and assumptions are standard, social scientists must use them cautiously and rigorously.

It's clear to us that adversarial collaborations have much to offer science and exemplify the spirit of honest scientific inquiry. Yet more than two decades after Kahneman coined the term "adversarial collaboration" and hoped these procedures would become standard, the practice remains rare, and its promise is still largely theoretical.

There are many legitimate reasons for the dearth of adversarial collabo-

QUICK TAKE

Contradictory findings persist in social sciences, undermining validity, reliability, and public trust in research. Practices such as open science cannot fully address this problem.

Entrenched positions result from a system that rewards novelty, supports fiefdoms, and disincentivizes publishing null results and reproducibility studies.

Adversarial collaborations offer a neutral framework for resolving disputes and mutually publishing findings, but they require wider adoption to be effective.

Yuki Murayama

Researchers who have reached contradictory conclusions around an issue can feel separated by an uncrossable gulf—a chasm widened further by unconscious or unacknowledged biases. Adversarial collaborations offer a constructive way to bridge that gap.

rations. Participating requires that scientists relinquish some of their autonomy to accommodate the preferences of others. These collaborations also require navigating the logistics of choosing team members, agreeing to schedules, and negotiating a host of methodological disagreements with adversaries.

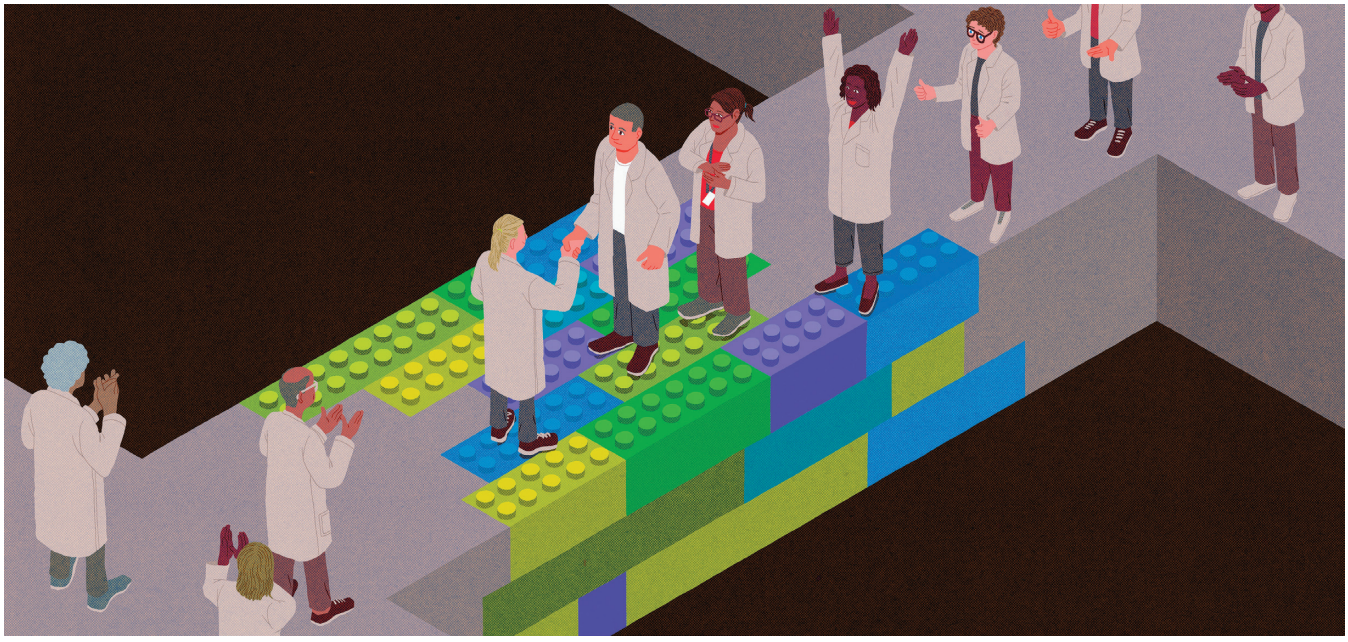
Yet, as contradictory claims accumulate, the need for adversarial collaborations grows deeper. This necessity is especially pronounced in many social sciences, where we see divergent findings coexist and receive empirical support over very long periods, sometimes over entire careers. One team will publish a finding that another team counters with a contrary finding, and this back-and-forth can go on for decades. Or, worse, the two contrary lines of scholarship occur in parallel, but the advocates for one side only rarely grapple with the issues raised by the other. We believe this pattern is partly due to misaligned incentive structures in science that reward novelty, which often requires contradicting prior work. We believe adversarial collaborations can also overcome these impasses.

The alternatives leave much to be desired. Occasionally, a resolution of contradictory claims results from the retirement or death of a key proponent rather than stemming from a deep resolution among scientists. As German physicist Max Planck wrote in his 1949 work, *Scientific Autobiography and Other Papers*, "A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." This is unquestionably an embarrassing situation for science. Must someone really retire or die for scientists to relinquish our cherished theories?

Reliability and Validity

Using adversarial collaborations, we can do better—not only by settling disputes more scientifically than, as Planck is sometimes paraphrased, "one funeral at a time," but also through the selection of tests by which we settle disputes. We speculate that teams comprising divergent scholars are likelier to use philosopher Deborah Mayo's concept of *strong inference*, defined in her 2018 book *Statistical Inference as Severe Testing*, and *severe testing*, Mayo's term for the powerful hypothesis-testing methodology described by the late physicist John R. Platt in his seminal 1964 *Science* paper, "Strong Inference." Strong inference refers to setting up a test between mutually exclusive predictions and publishing the findings regardless of the results, rather than what we fear has become the norm: seeking confirmatory evidence and "file drawering" null results (again, this state of affairs is not entirely scientists' fault; null results are notoriously difficult to publish). Beyond the rare "existence proof" (for example, how finding a single black swan disproves the claim that all swans are white), no single social science study can conclusively refute any particular theory; scientific claims frequently involve boundary conditions and zones of uncertainty. Nonetheless, we see value in comparing predictions made by competing theories to determine which one has a more successful track record.

Severe testing is the related idea that the scientific community ought to accept



Yuki Murayama

By negotiating mutually agreed-upon research methods and judgment criteria, teams in adversarial collaborations can bridge ideological and methodological divides, producing a robust finding that is potentially more rigorous, reproducible, and valid than their individual efforts.

a claim only after it surmounts rigorous tests designed to find its flaws, rather than tests optimally designed for confirmation. The strong motivation each side's members will feel to severely test the other side's predictions should inspire greater confidence in the collaboration's eventual conclusions. If such procedures became mainstream, scholars might adopt more rigorous standards at the outset to preempt such challenges.

Some readers may wonder if the more recent and popular practices called *open science*, which include openly sharing data and materials and publicly preregistering research plans before collecting data, might not address some of these concerns. Preregistration refers to the practice of creating a written, publicly available document that lays out a study's hypotheses, methods, and planned analyses, and that discusses how scientists will interpret results with respect to (dis)confirmation of these hypotheses. We strongly support open science practices. They help improve science's reliability—our confidence that, when we use the same methods again, we will obtain similar results. Moreover, transparency reduces opportunities for the kinds of scholarly wiggle room (dropping cases or variables, for example) that previously enabled the reporting of statistically significant effects from null datasets.

But adversarial collaborations address a different, possibly more serious problem than reliability: validity. We know that science suffers from a validity crisis because countless scientific papers directly contradict each other. Under the rules of Aristotelian logic and Popperian falsifiability that characterize most modern science, such contradictions mean that many scientific conclusions, replicable or not, must be incorrect. Adversarial collaborations can help address this problem by letting scientists merge perspectives over time and identify critical boundary conditions that lead to more unified understandings.

Open science, moreover, lacks safeguards against bias. Good scientists strive to avoid bias, but as cognitive and social psychologies remind us, such prejudices can occur unconsciously and persist unrecognized. Bias can result from the typical lack of viewpoint diversity among collaborators because like-mindedness often prevents team members from considering key issues. Importantly, bias resulting from such viewpoint "bubbles" can occur even among team members who use the most common and well-known open science practices—such as preregistering hypotheses, methods, power analyses, and statistical procedures, and making raw data publicly available—because such initiatives place no constraints on how scientists select methodological procedures. Preregistration does not require that a team include a devil's advocate who will propose alternative hypotheses, dependent variables, operationalizations of core constructs (how to make concepts testable or measurable), or methodologies. Nor does it demand that someone strive to falsify rather than to confirm.

In short, unlike adversarial collaborations, open science practices do not involve implementing severe tests or selecting team members to disagree over what evidence would disconfirm a theory. Thus, though laudable, these practices do not address biases or other key shortfalls the way that adversarial collaborations can.

Sociopolitical Implications

Beyond resolving long-standing scientific disagreements, we believe that adversarial collaborations could increase both the validity and credibility of scientific conclusions with important sociopolitical implications, such as gender bias in tenure-track hiring. Based on the contents of top science journals such as *Nature* and *Science*, findings by blue-ribbon National Academies of Sciences, Engineering, and Medicine commissions, and articles in respected legacy media such as *The New York Times*, one might assume that gender bias in academia is settled science, and that women are less likely than men to be hired, promoted, published, or rated as competent.

If, as some studies suggest, social psychology has undergone a homogenization of political views—or, in any case, if one accepts the assertion that research is often conducted by teams of people

who share the same views regarding the research topic—then it follows that hypotheses that challenge the assertion of gender bias in tenure-track hiring will face an uphill battle before anyone can pose, test, and publish them (assuming they ever do so). If so, then the existence of tenure-track gender bias might be either a valid finding or merely a concrete manifestation of the social sciences' lack of viewpoint diversity. We do not intend to adjudicate this question here; rather, we seek to shine a light on how research can become ideologically thorny when it lacks a mechanism such as adversarial collaboration to help resolve contradictory conclusions.

Indeed, an adversarial collaboration two of us published with economist Shulamit Kahn of Boston University in *Psychological Science in the Public Interest* in 2023 attempted to resolve formerly published contrary findings on this very topic. Our results showed that gender bias claims in academic sciences are often incorrect or lack needed qualifications. In our view, representation from different viewpoints can help elucidate this topic and others with sociopolitical implications, such as studies of affirmative action, gender bias, abortion, DEI (diversity, equity, and inclusion) attestations, implicit racism, and immigration.

To take one example, various controversies beset the notion of implicit bias (unconscious or unrecognized prejudice), including how strongly such bias predicts discrimination, whether measures of it differ from explicit prejudice, whether implicit trainings do more harm than good, and whether scores of 0 on the Implicit Association Test (an assessment tool for detecting belief associations and implicit bias) in fact correspond to egalitarian attitudes. Similar controversies surround topics such as the role of racism in policing; microaggressions; the relative prevalence of biases among those on the political right versus the political left; the effectiveness of gender-affirming care; the magnitude and importance of sex differences; the predictive validity of standardized achievement tests; and the validity of various low-cost interventions in academic achievement.

For such politically charged issues, adversarial collaborations might also help repair ongoing declines in scientists' credibility among the public. Over the past two decades, aside from a small recent uptick, trust in academia has been declining among conservatives. As Morgan Marietta and David C. Barker argue in their 2019 book, *One Nation, Two Realities*, the more Americans across the political spectrum become aware of the left-leaning skew within academia, the less credible they find claims made by its members. And recent research suggests that the apparent politicization of scientific journals and programs undermines public trust in those institutions and saps the public's willingness to defer to scientists' expertise.

We hold that scientists might earn back that trust through the improved validity made possible by adversarial collaborations. That validity stems partly from the improved rigor we expect will result from negotiating methods with contrary team members, and partly from a tendency of adversarial collaborations to limit confirmation biases and reduce leaping to unjustified conclusions.

Teams of rivals were able to greatly narrow their differences because of discussions with opposing team members.

Consider, for example, an adversarial collaboration concerning the effects of accuracy prompts, which ask users to evaluate the trustworthiness of a source or the correctness of a headline, on the quality of news-sharing decisions (and potentially the spread of misinformation). Published in a *Psychological Science* paper in 2024, the collaboration addressed a disagreement among researchers regarding whether such prompts work on politically right-leaning audiences—an important question, because research suggests that Americans on the right are more likely to share misinformation. To test the question, the authors used a multiverse meta-analysis, which subjects data to a full range of possible analytical decisions a researcher might make, thereby testing how sensitive that data might be to various analytical choices. The authors found that party membership did vary the effectiveness of accuracy prompts, but that the weakness of the effect among Republicans was not consistent and depended on "operationalizations of ideology/partisanship, exclusion criteria, or treatment type."

Team members who acknowledge such uncertainties will reach conclusions that are more valid than more blinkered team members who erroneously believe their evidence is compelling. Moreover, as adversaries articulate their competing perspectives, they may find that their disagreements are much smaller than they originally thought. In a 2024 article in *American Psychologist*, we described several cases in which teams of rivals were able to greatly narrow their differences because of discussions with opposing team members.

We believe that adversarial collaborations can also create synergies with other best practices and approaches, including preregistration. Good science can benefit enormously from this public airing because it minimizes post hoc claims that undermine scientific validity. Consider two notable preregistration variants: registered reports (RRs) and registered replication reports (RRRs). In the former, authors submit a preregistration to a journal or review platform (such as the Peer Community in Registered Reports) for consideration. The journal can offer an in-principle acceptance: If the authors conduct the study and interpret it as described, the journal will likely publish it. Such reports address publication bias because the journal will publish the research whether the results are significant or not, and without regard for any theoretical or political position the findings might refute. RRRs work the same way, except they are proposed replication studies. Both variants work well with adversarial collaborations, which can help ensure their fairness and rigor. For their part, RRs and RRRs can help hold adversarial collaborators to an explicit research plan that minimizes postgame quarreling.

A New Standard

Our research and our experience indicate that the significance of adversarial collaborations extends well beyond any one specific outcome. More important than whether the individual adversaries change their theories, we argue, is the opportunity the entire scientific community will gain to evaluate the findings produced by an adversarial collaboration team—a

structured, rigorous review of competing predictions derived from those theories. As the Hungarian philosopher Imre Lakatos and others have argued, scientists view a theory as plausibly debunked not when its most prestigious or aggressive proponents admit to its refutation, but when the community of diverse scholars reaches a consensus that the theory is useless, of extremely limited value, or debunked.

Neither adversarial collaborations nor preregistrations are guaranteed to solve these or any other empirical or theoretical controversies. However, we contend that the synergistic combination of adversarial collaborations and preregistered reports comes as close as the field currently can to such a standard. And, as Nelson Cowan argued in the *Journal of Applied Research in Memory and Cognition* in 2022, preregistered adversarial collaborations should advance psychological science more effectively, rigorously, and quickly than any known alternative.

Consider a parallel notion common in the tech sector, which has long employed "red team" members in research to play devil's advocate and to find flaws in computer programming code. Red team members function much like the opposing members of an adversarial collaboration. Traditionally, programmers and mechanical engineers prototype and seek all ways to break their own code and dismantle their creations because they realize that, once released, someone else will most definitely try to defeat them.

Even if they improve psychological science, adversarial collaborations have their limits, many of them human. Any member of any team of theoretical or political adversaries may still retain their own limitations, biases, or blind spots. Thus, whatever the team members produce can and should remain subject to evaluation by conventional scientific standards, including the wider community of scholars and scientists.

Moreover, convincing opposing sides to join adversarial collaborations can pose a challenge. Each side has much to lose if the findings undermine their past claims, which may form the very foundations of many of their careers. But there is also a powerful incentive for scientists to join adversarial collaborations: If they decline the invitation, someone else with less at stake—someone who may not advocate as diligently for their past claims—may take their place. Of course, researchers who join an adversarial collaboration may actively work to find loopholes, undermine their critics, or even sabotage the process to preserve their favored positions.

Adversarial collaborations can increase both the validity and credibility of scientific conclusions with important sociopolitical implications.

However, participants can substantially curtail the power of these bad actors by establishing safeguards and protocols up front, such as appointing a neutral referee to adjudicate internal disputes.

With all of these factors in mind, we propose the establishment of an infrastructure within journals or externally that will support and encourage conflicting perspectives, emphasizing adversarial collaborations but also utilizing other mechanisms (such as RRRs) that infuse studies with opposing voices. Particularly when the research question concerns a highly contentious topic or a weighty sociopolitical issue, the members of each adversarial collaboration team should represent the competing views or ideological positions that are most affected. Ideally, funding tracks specific to adversarial collaborations might be established within funding bodies for particularly controversial or high-stakes research questions. Research agencies might implement a funding bonus on top of regular grants for authors who accept the risks of working across the aisle with rivals or opponents. Journals might establish dedicated article tracks. Finally, the infrastructure should include a means of commissioning retrospective meta-studies to determine whether adversarial collaborations do in fact score higher on validity and reliability.

The University of Pennsylvania is home to one such nascent effort: the Adversarial Collaboration Project. Project members are currently carrying out multiple adversarial collaborations, including on the issues of motivated reasoning, implicit bias, and political bias in psychology, and have collaborated with a few academic journals, including *Advances in Methods and Practices in Psychological Science*, to promote adversarial collaboration research. But the project is still small and new, and adversarial collaborations will require broader buy-in from the entire scholarly community.

We can do better. If research teams included scholars with opposing research agendas, the social sciences would likely see stronger inferences and more severe testing, thereby optimizing methods and producing better science. Adversarial collaborations are an idea whose time has come, and their commissioning could lead to a much-needed cultural shift in science.

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Perspective

Seasons of Change

Foraging communities of the past and present demonstrate a social fluidity that is absent in many modern community structures.

Cecilia Padilla-Iglesias

If you ask a BaYaka forager in the Central African rainforest, "Where do you live?," they often reply with a question of their own: "*Mouanga* or *Pela*?"

You'll get the same response to nearly any question about their lives: Who do you live with? Who is this camp's leader? How do you mourn the dead?

"*Mouanga* or *Pela*?"—meaning, "Dry or wet season?" The BaYaka's social world shifts throughout the year. The location and size of their homes, the materials used to build them, leadership, funerals—all transform depending on the season.

As an evolutionary anthropologist working with the BaYaka, I initially presumed people simply adjust because of the seasonal availability of different foods. But their changes extend way beyond sustenance into the realms of politics, economics, rituals, and relationships.

These shifts starkly contrast with those of my homes in the United Kingdom and Spain, countries seemingly locked into fixed sociopolitical and economic orders. BaYaka flexibility made me rethink my assumptions about what is "natural" for human societies, including gender roles, hierarchies, and social group sizes.

And the more expansively I looked, I realized BaYaka flexibility isn't the anomaly: The rigidity of industrialized, capitalist societies is. Across history and geography, societies have restructured their sociopolitical and economic lives in response to seasonal shifts—and perhaps not solely due to fluctuating resources. People may also do so because they recognize the dangers of stagnation.

As I see it, regular restructuring keeps communities adaptable and resilient. Solving today's greatest challenges—such as inequality, authoritarianism, and the climate crisis—may require embracing this flexibility as part of the fabric of our societies.

Categorizing Societies

Humans, for most of our existence, have lived as hunter-gatherers. Today, only a small number of societies still rely on foraging. But studying how these groups adapt to different environments helps evolutionary anthropologists understand how our species became so widespread and successful.

Like our great ape relatives, human foragers often live in what anthropologists call *fission–fusion societies*—fluid systems in which groups come together or split apart depending on the availability of resources. But for chimpanzees, territorial boundaries and rigid dominance hierarchies constrain the possibilities for various social arrangements. Humans, on the other hand, can negotiate their relationships through language, shared conventions, and cultural institutions. This capacity allows for more flexible—and often more egalitarian—forms of social life.

Despite acknowledging this flexibility, many anthropologists and archaeologists have historically classified societies into fixed types. One of the most influential models, developed by cultural anthropologist Elman Service in the 1960s, proposed four categories: bands, tribes, chiefdoms, and states. In this framework, small, mobile foraging groups (bands) are seen as the most basic form of social organization. With time, societies develop into tribes, then chiefdoms, and finally states—along the way becoming larger, settled, and hierarchical. The progressive nature of this model suggests that those qualities make a society more complex.

Over the years, many have questioned and challenged this model: Today's anthropology textbooks might mention it as a historical note, rather than a lesson on current thinking. But Service's basic logic lingers, influencing how both researchers and broader publics tend to view human history: as an inevitable linear progression from mobile to sedentary, egalitarian to hierarchical, simple to complex.

This thinking appears in archaeology too. When researchers uncover changes in tools, architecture, or other archaeological objects, they often assume earlier inhabitants were replaced by outsiders. The newcomers—who were more advanced in some way—would bring a different social structure, which could be neatly slotted into one developmental stage or another.

QUICK TAKE

Many foraging peoples, such as the BaYaka in Central Africa, alter their social structures with the seasons to meet different community needs.

For most of human history, it was common for societies to have flexible social hierarchies and practices. This adaptability allowed humans to thrive in different environments.

Static social structures are not an inevitable progression of human society. These fixed hierarchies deepen inequality and have no built-in mechanism to reset the balance.

Novarc Images/Nicolás Marino/Alamy

During the wet season in Central Africa, the BaYaka people travel and forage in small groups, but during the dry season they gather in larger communities where they fish and grow manioc. As the groupings change with the seasons, so do the social dynamics: Leaders in one environment may take more passive roles in another, for example. Migration and shifting societal roles were common throughout most of human history; the current, relatively stable power structures of the industrialized world are anomalous and are not an inevitable progression in human society.

I also carried these assumptions into my first field trip with the BaYaka. I arrived in the rainforests of the Congo Basin expecting to find one fixed type of society.

Seasonal Shifts

Anthropologists working with the BaYaka have often characterized them as egalitarian hunter-gatherers. The researchers report that the BaYaka live in small, mobile camps and survive primarily on wild yams, honey, and animals such as blue monkeys.

But when I visited the BaYaka in 2023, I witnessed more variation in their lifestyle, depending on the time of year. In February, the communities live in large aggregations near villages, growing manioc and fishing. A few months later, when rains return, these settlements dissolve, and groups of fewer than 15 disperse into the forest to gather honey, caterpillars, and mushrooms.

These shifts in subsistence strategies mean more than just a change in diet: They require entire social reorganizations. Leadership, cooperation, and even spiritual life transform with the seasons. Rituals that unite hundreds of people in the dry season become intimate practices among close relatives and friends in the wet season. Some rituals—such as *Eboka*, which commemorates a relative's death—only occur during the dry season.

And the BaYaka aren't unique in their cyclical shifts. The 20th-century French anthropologist Claude Lévi-Strauss documented seasonal transformations among the Nambikwara, an Indigenous Amazonian group whose territory today lies in central Brazil. For five months each year, according to Lévi-Strauss, they inhabited large villages, tending small gardens for food. When the dry season began, they dispersed into smaller, mobile foraging groups. These shifts also ushered in a reversal of political authority. During the dry season, leaders became authoritative decision-makers, resolving conflicts directly. When the rains returned, the same leaders no longer held coercive power. They could only attempt to influence through tactics such as gentle persuasion or caring for the sick.

Similarly, at the turn of the 20th century, anthropologist Franz Boas observed that inequality peaked during the winter among the Kwakiutl, or Kwakwaka'wakw, a First Nations people along the Pacific Coast of what is now Canada. Boas wrote about Kwakwaka'wakw winter villages with strict hierarchies and grand ceremonial events. In summer, these rigid structures dissolved as communities broke into smaller, more flexible groups. And rather than people dividing subconsciously solely to adapt to the weather, they were so aware of the political nature of their practices that individuals even changed names when they adopted new social positions for winter ceremonies.

Meanwhile, in my home countries and many others today, institutions seem immutable, changing only during revolutions, coups, or wars.

Losing Equality

Last January, many watched U.S. President Donald Trump's inauguration, backed by three men whose combined wealth exceeded that of the poorest 50 percent (more than 165 million) of people in the United States. Unlike seasonal hunter-gatherers, whose social orders regularly reverse, most people in the so-called Western world now live in systems where inequality deepens continuously, with no built-in mechanism to reset the balance.

As scholars deeply concerned with the roots of inequality, the late anthropologist David Graeber and archaeologist David Wengrow asked in their 2021 book *The Dawn of Everything*:

> How did we get stuck? How did we end up in one single mode? . . . How did we come to treat eminence and subservience not as temporary expedients, or even the pomp and circumstance of some kind of grand seasonal theatre, but as inescapable elements of the human condition?

Many scholars trace inequality's roots to the advent of agriculture, arguing it "locked in" social hierarchies. The logic is straightforward: Farming allows people to settle in one place and accumulate surplus food and other goods, setting the stage for haves and have-nots. Archaeologists have long assumed this emergent inequality coincided with the appearance of features such as elaborate burials or grand monuments. Such structures would exist to celebrate powerful people and require a central authority to command their building, the thinking goes.

But perhaps the archaeological record tells a more complicated story.

Long before farming, during the last ice age, people were already building big. As early as 18,000 years ago, along the glacial fringe from Krakow to Kyiv, hunter-gatherers constructed circular houses out of mammoth bones—structures that some archaeologists describe as early forms of public architecture. These settlements weren't occupied year-round, based on the presence of bones from seasonally available animals. They appear to have been seasonal aggregation sites, built and occupied temporarily when dispersed groups came together to cooperate, share resources, perform rituals, and then disperse again.

More famously, the massive stone enclosures at Göbekli Tepe in southeast Turkey (often described as "the world's first temple") were built over 11,000 years ago by foragers. There is no evidence that the site was permanently inhabited, nor that it was the product of some big societal turnover, such as new migrants or the start of farming. Like the mammoth-bone houses, it may have been a seasonal gathering center built by communities who came together temporarily to create something extraordinary—then walked away.

These cases flip the usual narrative. Instead of assuming that hierarchy is the prize of complexity, these sites suggest that not all monumental architecture required a ruling class. For much of human history, societies didn't follow a single political trajectory—they shifted between different modes of organization, much like the BaYaka do today.

Recognizing humanity's long tradition of social fluidity puts the present into perspective: The Western world is not the culmination of a 10,000-year-long march but an anomaly in a 300,000-year-long history of *Homo sapiens*' cultural adaptability.

Reclaiming Seasonal Flexibility

Humans have long managed to restructure their societies with the changing seasons, refuting the narrative that inequality is an inevitable endpoint for us all.

For much of human history, societies didn't follow a single political trajectory—they shifted between different modes of organization, much like the BaYaka do today.

But my point is not that seasonal environments forced humans to remain flexible, and therefore, without seasonality, flexibility wouldn't exist. Rather, it's that regularly coping with radically different conditions allowed people to experiment with diverse social and political arrangements. In turn, this adaptability underlies our species' ability to thrive in almost every ecosystem on Earth.

As Wengrow and Graeber also emphasized, seasonal shifts have no set pattern. The largest rituals occur during the dry season for the BaYaka but during the wet season for the Nambikwara in Amazonia. Among Gabbra pastoralists of northern Kenya, lunar cycles, rather than weather, determine the holy seasons of Soomdeer and Yaaqa, as an elder revealed to me recently.

Even in industrialized societies, echoes of this flexibility persist. Consider the "holiday season" in capitalist countries with many Christians. Most of the year, individualism dominates. But each December, work slows and social traditions encourage generosity, community, and connection—briefly perturbing the usual social order. Historically, similar seasonal reversals occurred during Roman Saturnalia, medieval carnivals in Europe, and global May Day celebrations. Hierarchies were temporarily subverted, and alternative forms of social life were explored.

Humans have always possessed the ability to imagine and enact different social arrangements. Take any two contemporary chimpanzee communities, and their social organization will look similar—both to one another as well as to chimp groups from the last century. Compare contemporary societies such as those of the United States and the BaYaka, and they could hardly be more different. Yet both represent active possibilities in the human political imagination.

No social order is inevitable. No structure of power or inequality is fixed. Adaptability has defined our species since its origins. For societies that seem stuck, reclaiming flexibility might be the greatest challenge—but also the solution to their existential afflictions.

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On a Wing and a Prayer?

A century after the Scopes trial, a look back shows the development and folly of creationist supernatural engineering.

Robert T. Pennock

On July 21, 1925, in Dayton, Tennessee, a verdict was reached in what became known as the "trial of the century": High school teacher John Scopes was found guilty of violating Tennessee's Butler Act, which forbade public schools from teaching "any theory that denies the story of the Divine Creation of man as taught in the Bible, and to teach instead that man has descended from a lower order of animals." The infamous "Monkey Trial," as it was commonly called, had begun as a stunt by town leaders to bring attention to their community—one newspaper comic depicted Dayton as an organ grinder whose monkey raked in cash and publicity—but it quickly evolved into what is now thought of as the start of America's 100-year culture war.

Scopes himself was a bit player in the courtroom battle between two nationally known figures: defense attorney Clarence Darrow representing modern science, and prosecutor William Jennings Bryan representing traditional religion. Each day of the trial began with a public prayer from an invited minister, and the presiding judge overruled the defense's objection that these prayers prejudiced the case, saying "I believe in prayer myself; I constantly invoke divine guidance myself. . . . I see no reason why I should not continue to do this." The judge allowed Maynard Metcalf, a zoologist from Johns Hopkins University, to testify about the scientific basis of evolution, but he barred the eight other expert witnesses whom Darrow had brought in. Most notably, he allowed Bryan himself to testify as an expert witness on the Bible. Darrow's cross-examination of Bryan became the centerpiece of the trial.

Scopes himself was a bit player in the courtroom battle between two nationally known figures: Clarence Darrow representing modern science, and prosecutor William Jennings Bryan representing traditional religion.

The spectacle of their confrontation was later dramatized in the play and movie *Inherit the Wind*, which used the *Scopes* trial to symbolize the Communist "witch hunts" of 1950s America led by Wisconsin senator Joseph McCarthy. But the trial has always been seen as emblematic of science versus religion, a conflict that remains as unresolved as the trial itself. In the end, Scopes was fined $100, but the way the fine was levied led to the verdict being overturned on a technicality. The state of Tennessee repealed the Butler Act in 1967, but other anti-evolution laws remained on the books in other states until the Supreme Court ruled that they were unconstitutional in *Epperson v. Arkansas* in 1968.

From Dayton to Dover

In the decades that followed *Epperson*, creationists tried to attack evolution in other ways, all without success. Their first strategy was to demand equal time in the classroom. The 1975 *Daniel v. Waters* federal court case overturned a Tennessee law that had required any textbook that included evolution to state that evolution was not to be taken as a scientific fact and to give equal emphasis to other theories, including the Genesis account, with the Bible as a reference work (though without a similar disclaimer about Genesis not being taken as fact).

In *Segraves v. California*, a 1981 Superior Court of California case, the presiding judge rejected a claim put forward by Kelly Segraves, a cofounder of the Creation-Science Research Center, that evolution should not be taught because doing so was an establishment of "the religion of secular humanism" and violated his children's rights to

QUICK TAKE

A century ago, *The State of Tennessee v. John Thomas Scopes* trial kicked off what is now thought of as America's 100-year culture war centering on evolution and creationism.

The most recent trial in this series was *Kitzmiller v. Dover Area School District* in 2005, which found that teaching intelligent design in public schools violated the U.S. Constitution.

Examining the arguments of intelligent design through the lens of engineering and genetic algorithms can debunk the idea that complexity requires divine intervention.

religious freedom. Calling science religion doesn't make it so.

Of course, it is significant that creationism is not representative of all religion but is a particular religious view that itself comes in many varieties. All creationists reject evolutionary science in favor of some form of supernatural creation, but even these classic cases involved different fundamental positions. Creation-science removed reference to the Bible, but kept what it took to be the key elements of the Genesis account: not only separate ancestry of humans and apes, but also the abrupt creation of the world and all lifeforms from nothing at a time in the recent past—over the course of a week some 6,000 to 10,000 years ago.

As part of my research on creationism, I observed this "Young-Earth" view promoted in a rousing event put on at a local evangelical church by creationist Ken Ham's Answers in Genesis ministry. Ham is best known today for the Ark Encounter creation theme park he founded in Kentucky, which features a full-size representation of Noah's Ark. (Creationism opposes not only evolution, but also rejects basic findings of other sciences. For instance, creation-science explains Earth's geology by catastrophism, including a worldwide flood.) Young-Earth creationism is the most prominent form today, but "Old-Earth" creationists have different hermeneutic interpretations of the Genesis days of creation that allow them to accept the geological scale. In the *Scopes* trial, Bryan held an Old-Earth position.

The next strategy was to try to claim that creationism is science. Creationists enacted laws that required "Balanced Treatment for Creation-Science and Evolution-Science." Two cases, one in Arkansas in 1981 and one in Louisiana in 1987, rejected creation-science as disguised religion, the latter case having made its way to the U.S. Supreme Court, which overturned the "balanced treatment" laws as unconstitutional. Calling religion science doesn't make it so.

Undeterred, creationists again set out to retool their approach. The most recent major court challenge occurred in Dover, Pennsylvania, where the local school district had introduced "intelligent design" (ID) as an alternative to "Darwinism." The 2005 *Kitzmiller v. Dover Area School District* federal case, which challenged the school board's policy, was called "Scopes II" or the "Dover Panda Trial" in the press, referring to the intelligent design textbook *Of Pandas and People* that was at issue. I was one of several expert witnesses during this trial because of my research on creationism.

Watson Davis/Smithsonian Institution @ Flickr Commons; Wesley Elsberry/NCSE

In 1925, the *Scopes* trial was moved outside because of the heat. There, Clarence Darrow continued his cross-examination of William Jennings Bryan, as Bryan defended the Bible over evolution, in front of large crowds (*top*). In 2005, the *Kitzmiller* trial in Dover, Pennsylvania, similarly attracted vast interest from the public. The media at the trial crowded and jostled some of the plaintiffs, Tammy Kitzmiller and Beth Eveland, for comments (*bottom*). The *Kitzmiller* case centered on the intelligent design textbook *Of Pandas and People*, so it was sometimes referred to as the "Dover Panda Trial" in press reports.

Postmodern Creationism

The ID movement included both Young-Earth and Old-Earth creationists, but its strategy was to remain silent regarding the age of the Earth and to unite the different factions under a minimal banner of "mere creation." Their approach was that arguments about the age of the Earth could continue after they had destroyed the evolution-based foundation of science's modernist, naturalistic worldview.

The choice between natural evolution and supernatural creation can be reduced to the problem of explaining complex biological features such as bird wings. ID creationists changed the terminology, but in this sense their fundamental beliefs were continuous with those of creation-science. No

Issuing Rebuke, Judge Rejects Teaching of Intelligent Design

By LAURIE GOODSTEIN

HARRISBURG, Pa., Dec. 20 — A federal judge ruled on Tuesday that it was unconstitutional for a Pennsylvania school district to present intelligent design as an alternative to evolution in high school biology courses because it is a religious viewpoint that advances "a particular version of Christianity."

In the nation's first case to test the legal merits of intelligent design, the judge, John E. Jones III, issued a broad, stinging rebuke to its advocates and provided strong support for scientists who have fought to bar intelligent design from the science

"breathtaking inanity" and "dragged" their community into "this legal maelstrom with its resulting utter waste of monetary and personal resources."

Eleven parents in Dover, a growing suburb about 20 miles south of Harrisburg, sued their school board a year ago after it voted to have teachers read students a brief statement introducing intelligent design in ninth-grade biology class.

The statement said that there were "gaps in the theory" of evolution and that intelligent design was another explanation they should ex-

Bryan College; AP Photo/Carolyn Kaster; *New York Times*

In 1925 Dayton, Tennessee, John Scopes walks toward the courtroom with attorneys John Neal and George Rappleya (*left*). In 2005 Dover, Pennsylvania, science teacher Steve Stough and plaintiff Tammy Kitzmiller walked toward a similar courtroom with attorney Eric Rothschild and the author, who was an expert witness in the trial (*top right*). As indicated in a *New York Times* article after the verdict (*bottom right*), the judge ruled that intelligent design was not science.

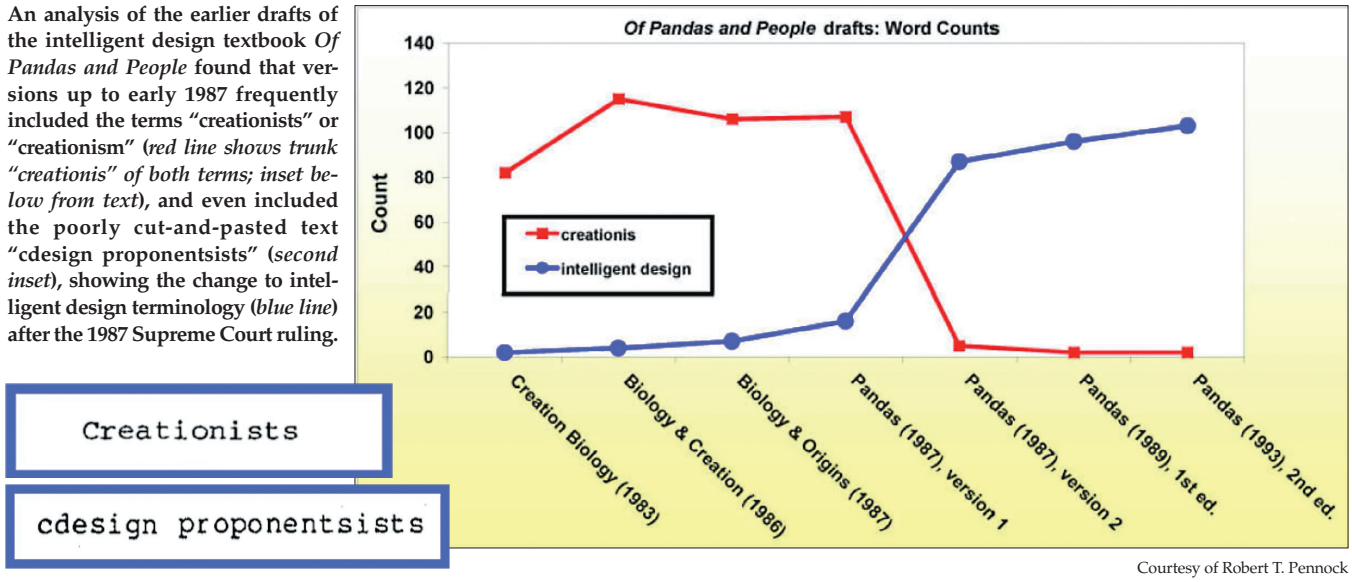
time frame was mentioned, but the notion of abrupt creation remained in the textbook. *Of Pandas and People* explained this core element of their view in this way:

> Intelligent design means that various forms of life began abruptly through an intelligent agency, with their distinctive features already intact—fish with fins and scales, birds with feathers, beaks, and wings, etc.

Proponents regularly denied that intelligent design was creationism, but research revealed that earlier versions of this passage were written exactly the same but had said "creation" instead of "intelligent design," and used the term "the agency of an intelligent Creator" instead of the more ambiguous "an intelligent agency." Wesley Elsberry, a data scientist at the National Center for Science Education, did a systematic analysis for the trial of the half dozen drafts of the textbook that the prosecution uncovered in the legal discovery process, revealing systematic changes from creationist to intelligent design wording. The terminological shifts occurred between a draft from early 1987 and one at the end of that same year—the year that the Supreme Court had ruled creation-science laws as unconstitutional. Expert witness Barbara Forrest, a philosopher at Southeastern Louisiana University, found the transitional form "cdesign proponentsists" in the second 1987 draft, a clear example of the cut-and-paste job that intelligent design creationists had done.

Establishing that intelligent design was continuous with previous forms of creationism was important because *Kitzmiller,* like all the cases after *Scopes,* involved a core feature of the American legal framework. The First Amendment of the U.S. Constitution's Bill of Rights includes protections for freedom of religion by prohibiting the government from establishing preferential treatment for any religion over another (the Establishment clause) and for setting prohibitions on religious expression (the Free Exercise clause). ID leader Phillip Johnson, a University of California, Berkeley, law professor whose conversion as an adult to Christianity led him to question evolution, thought that he had found a way to evade previous decisions on creationism that would set the stage for a renewal of Christian theism as the foundation for science, culture, and law. Taking inspiration from postmodernism, which rejected science as having any privileged way to discover truths about the world and analyzed knowledge in terms of power and narrative, Johnson wrote a book that he originally titled *Darwin Deconstructed*, but to avoid esoteric philosophy and emphasize his legal expertise, his publisher brought out the book with the title *Darwin on Trial*.

All of these legal issues are interesting in their own right, but they are irrelevant to whether it is proper to reconceptualize science to include supernaturalism. Creationism shouldn't be taught in science classes not because of legal prohibitions (which, anyway,



An analysis of the earlier drafts of the intelligent design textbook *Of Pandas and People* found that versions up to early 1987 frequently included the terms "creationists" or "creationism" (*red line shows trunk "creationis" of both terms; inset below from text*), and even included the poorly cut-and-pasted text "cdesign proponentsists" (*second inset*), showing the change to intelligent design terminology (*blue line*) after the 1987 Supreme Court ruling.

Courtesy of Robert T. Pennock

are unique to the United States) but because to do so would be, to use an engineering analogy, like substituting propellers with prayer wheels.

The Divine Engineer?

Johnson and his allies viewed modern science, and evolution in particular, as the linchpin of a metaphysically naturalistic worldview and saw intelligent design as a "wedge" to split it apart. They argued for a "theistic science" that would incorporate God into science in a substantive way. Like the creation-scientists, ID advocates argued that evolution could never explain the functional complexity of the world. Design, they said, required an intelligent designer.

Their philosophical argument for a supernatural designer is a variation of 18th-century Anglican clergyman William Paley's famous watchmaker analogy: Think of the spring motor and gears of a pocket watch whose arrangement serves to measure time. Just as that functional complexity must have been created by a watch designer, so too must the complexity of biological forms be traced back to a designer prior to, and superior to, nature itself. Paley used the watch and the vertebrate eye as key examples, but creationists see design everywhere. In the *Kitzmiller* case, the bacterial flagellum—whose complex arrangement of parts was likened to that of a propeller motor—was often brought up by the defense. Such creationist arguments are usually discussed just in relation to biological science, but it is equally revealing to consider them in relation to engineering. If we are supposed to teach theistic science, should we not also teach theistic engineering?

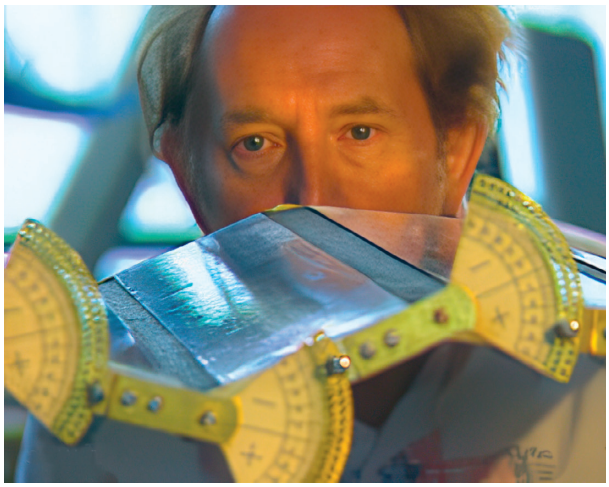
The idiom "on a wing and a prayer" was made popular in a World War II–era movie and song inspired by a true incident of a damaged plane with just one working wing engine that made it safely back to base. However, the phrase carries a mixed message: It conveys the idea of persevering with resilience in the face of challenging circumstances, but also the idea of doing so more on hope and faith than with a solid plan or adequate safety precautions. No one begrudges the pilot who told the crew to pray, but one would likely not blame God had the plane crashed. Engineers would be judged irresponsible if they tried to build God into their technology in a substantive way, expecting prayer to keep planes aloft. Methodological naturalism, an epistemological rule that disallows appeal to the supernatural, applies in engineering as well as in science. Aeronautical engineers' expertise involves building safe and efficient wing and engine designs; in engineering design work, atheist and believer alike must set possible divine intervention aside.

Aeronautical engineers' expertise involves building safe and efficient wing and engine designs; in engineering design work, atheist and believer alike must set possible divine intervention aside.

Creationists' arguments ultimately come down to claims that features of the world cannot be explained naturally by either chance or lawful mechanisms. But Darwin discovered the trick: Evolution does the engineering.

The Evolutionary Engineer

Comparative wing morphology is one kind of evidence adduced for common evolutionary ancestry. For example, pterosaurs, bats, and birds have similar body shapes that evolved independently for flight in different ways from vertebrate forelimb bones that have a common "one bone, two bone, many bones" structure (moving from torso joint to digits). Creationists regularly challenged scientists to provide evolutionary "missing links," and thus they have had to try to explain away fossil discoveries such as the 1861 uncovering of *Archaeopteryx*, which had three clawed digits on its extremities but also had broad wings with feathers like birds. Creationists claimed that *Archaeopteryx* was not a transitional fossil, but a unique, fully formed bird—or perhaps a forgery. Their key argument remained the same: An intelligent designer was still needed because no natural processes could engineer such complex, functional traits. However, Darwin's discovery was not just the evidence that evolution occurs, but



flickr.com/photos/dysanovic/2678713012/Wikimedia Commons; DW-TV

Engineer Ingo Rechenberg (*above*) pioneered certain forms of engineering with evolutionary methods. Here he is shown with an airfoil armature that has had its shape optimized by an evolutionary algorithm to reduce drag. Later, General Electric used genetic algorithms to design its GE90 engine (*right*), which had carbon fiber fan blades that achieved greater efficiency, lower weight, improved durability, and record-breaking thrust, and was recognized for its beautiful design.

also the natural mechanism—natural selection acting on heritable random variations—that engineers it.

Coincidentally, three engineers independently recognized that the evolutionary mechanism could be implemented in computer systems and applied to solve engineering design problems in the same way that it does in nature. I never had the chance to meet electrical engineer Lawrence J. Fogel, who pioneered what he called "evolutionary programming," but I did get to know University of Michigan electrical engineer John Holland, who developed "genetic algorithms" (GAs), and I was fortunate to meet and interview Ingo Rechenberg of the Technical University of Berlin, originator of "evolutionary strategies," when I was researching the history of the field.

Rechenberg was an aeronautical engineer, so some of his earliest experiments in the 1960s and 1970s investigated how evolutionary strategies could automatically produce forms important in the design of wings and motors. An initial proof-of-principle showed how natural selection could take a zigzag surface and smooth it to reduce drag. Later work demonstrated the evolution of featherlike wing tips, efficient bending designs for pipes, and two-phase jet nozzles that were useful for engines.

By the time of the *Kitzmiller* trial, evolutionary techniques were starting to become broadly applied in aeronautical engineering. To mention just one example, General Electric engineers used evolutionary techniques—yes, GE uses GAs—in the design of their revolutionary GE90 engine, which entered service in a British Airways 777 airplane in 1995. Its carbon-fiber-composite fan blades achieved greater efficiency, lower weight, and improved durability, with record-breaking thrust. For the beautiful design of GE's unusual blade shape, the Museum of Modern Art in New York City included one of the blades in its Architecture and Design collection. Evolution no longer creates only bird wings.

No divine intelligence was needed to engineer these functional designs, and it would be absurd to suggest that engineers should incorporate anything supernatural into their work.

Part of my testimony in the *Kitzmiller* trial was about my own work in evolutionary computation, which applies Darwin's law in computer environments, allowing it to be used for both experimental studies and practical applications. No divine intelligence was needed to engineer these functional designs, and it would be absurd to suggest that engineers should incorporate anything supernatural into their work. Some engineers may themselves be religiously devout, but "theistic engineering" is an oxymoron.

Inherit the Wind

Creationists believe that the Bible provides them with the expectation of a great inheritance, but their insistence on their own righteousness divides the community. During his cross-examination in the *Scopes* trial, Bryan argued that Darrow was trying to "slur at the Bible" and use the court to attack Christianity, but commentators generally agreed that it was creationism that troubled the household and would inherit the wind.

Creationists seem certain that they alone know (and know how) God intervenes in the world. However, numerous theological problems accompany such proclaimed "miracles," as they seem to involve a God who is inattentive, indifferent, ineffective, or far from impartial. Must passengers in a crashing plane be of the correct religion for their prayers to work? Or perhaps God is vindictively demonstrating power by making them ride the whirlwind? Televangelist Pat Robertson expressed this sort of view when he weighed in

on the school board election in Dover that was held shortly after closing arguments in the *Kitzmiller* trial concluded on November 4, 2005. All eight members of the board who had voted in the intelligent design policy were defeated in their reelection bids, and a Reuters news article reported that Robertson had warned of an evolution doomsday: "I'd like to say to the good citizens of Dover: If there is a disaster in your area, don't turn to God. You just rejected him from your city. God is tolerant and loving, but we can't keep sticking our finger in his eye forever. If they have future problems in Dover, I recommend they call on Charles Darwin. Maybe he can help them."

In the final scene of *Inherit the Wind*, the character who represents Darrow holds a copy of *On the Origin of Species* in one hand and a Bible in the other, and regards them separately before bringing them together as he exits the courtroom. "Theistic evolution" is the term for the theological view that religious belief is compatible with evolution, not in a creationist form but in its fully scientific sense.

ID creationists explicitly reject theistic evolution in practice and in principle. They view it as a contradiction in terms and as an ill-conceived accommodation to evolution. Their dual model argument depends on defining evolution and intelligent design as mutually exclusive and jointly exhaustive options, in the same way that creation-science was presented as the only alternative to evolution. Ironically, some atheists concur, but they draw the opposite conclusion—that belief in God is to be rejected in the same way one would reject belief in Santa Claus.

Clement Clarke Moore's poem "A Visit from St. Nicholas" depicts a wondrous supernatural visitation on Christmas Eve, as reindeer fly on the wind and St. Nick delivers toys and then, with a simple tap on his nose, miraculously flies up the chimney. That science rejects flying reindeer and nasal-triggered levitation does not obviate Moore's poetic imagery or threaten the comfort that believers may derive from prayers to the saintly protector of children and sailors. Multiple papal statements clearly represent the Catholic church's long-held position that there is no necessary conflict between evolution and their faith. Governing bodies of mainstream Christian denominations and other religions have issued similar statements, often in direct response to creationist claims during court cases.

Have we learned anything in the century since the *Scopes* trial? The *Kitzmiller* trial verdict suggests that we have. Its decision was handed down just before Christmas on December 20, 2005. The court ruled that intelligent design was not science but "creationism relabeled," and that teaching it in public schools violated the separation of church and state. It fined the Dover school district $2 million for the "breathtaking inanity" of including it. In his ruling, Judge John E. Jones III noted explicitly: "Defendants and many of the leading proponents of ID make a bedrock assumption which is utterly false. Their presupposition is that evolutionary theory is antithetical to a belief in the existence of a supreme being and to religion in general."

Governing bodies of mainstream Christian denominations and other religions have issued statements that there is no necessary conflict between evolution and their faith, often in direct response to creationist claims during court cases.

A Final Prayer for Earning One's Wings

In Frank Capra's classic 1946 Christmas film *It's a Wonderful Life*, Angel Second Class Clarence earns his first-class angel wings after saving George Bailey, by showing him the value of his life in contrast to how the world would have played out differently without him. Harvard paleontologist Stephen Jay Gould, who was an expert witness in the 1981 Arkansas case, used the film as a trope in his 1989 book *Wonderful Life*. The book emphasizes the role of chance and contingency in evolution, using the idea of "replaying the tape of life" to suggest how small changes could make the story turn out very differently. He critiqued teleological evolution, arguing against the idea that evolution inherently progresses toward greater complexity or purpose. Gould stated his thesis too broadly, and experimental evolution in natural and digital systems allows us to test and refine some of these ideas. Be that as it may, he was right that nothing about evolution precludes a life of meaning and purpose. Gould elsewhere advanced what he called the "NOMA" view, which holds that religion and science are "nonoverlapping magisteria," leaving room for spiritual purpose.

Of course, there are also agnostic and even fully atheistic paths to purposefulness. Finding meaning and saving lives may be done without angelic intervention. Engineers take on the task of doing just that, using natural science to build safer planes and other lifesaving technologies. They may even use the evolutionary mechanisms that Darwin discovered to do so.

STEM teachers who are also religious believers may be understood for offering a prayer that they be allowed to teach their subjects responsibly, and that scientists and engineers continue to reject supernatural shortcuts, but rather devote themselves to the hard work needed to earn one's wings.

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The Unlikely Primeval Sky

Of all the patterns that could possibly be preserved in the post–Big Bang radiation, the one we see is surprisingly smooth on large angular scales.

Craig Hogan

Sitting by a campfire on a dark night, looking up at the Milky Way, a curious child asks, "What does the sky tell us? Where does it all come from? Does space go on forever?" A caring adult might share a little awe and humility about humanity's place in the grand scheme or perhaps relate a traditional creation story. A scientist like me, who came of age soon after the discovery that the sky is not actually dark but awash in primeval radiation, might instead relate the still-unfinished scientific story of the boundaries and origins of time and space. That tale is displayed in nature's own record of the structure of the early universe, a mosaic of temperature and density fluctuations preserved in the primordial light that astronomers call the cosmic microwave background (CMB).

But this Big Bang campfire story includes a remarkable "just-so" twist: The seemingly random pattern of small CMB temperature variations seems specially arranged on the very largest scales, such that on average and in widely separated directions, the values almost exactly cancel out. It's as if all the parts of the universe "knew" what the other parts of the universe were like. Did matters just turn out that way, or is there more to the story?

The Big Bang was the incredibly hot, dense birth of the universe in which elementary and subatomic particles first fused into light elements and space itself began expanding. The CMB is relic radiation from about 380,000 years later, when conditions had cooled enough to become transparent and allow photons to travel freely. "Cool" is a relative term: What we measure as an apparent temperature of 3 kelvins due to cosmic expansion was in fact plasma around 1,000 times that hot. (A plasma is a soup of freely moving ions and electrons, like the solar wind or a star's interior.) Amazingly, the CMB remains visible today if we use instruments that separate the various spectra of light emitted by events throughout cosmic history.

If we could see the whole sky of radio- and millimeter-wavelength light, or microwaves, it would look something like the top image on page 356. This iconic map derives mainly from measurements by the Planck satellite, a craft launched by the European Space Agency in 2009 to study tiny CMB fluctuations. As with the Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP) before it, scientific circles and the popular press alike hailed Planck for its unprecedentedly detailed, precise, and effective estimates of the universe's age and composition.

In this image, the CMB is the uniformly mottled, wallpaper-like pattern of small, slightly warmer and cooler patches located at the top and bottom. The fluctuations it shows stem from minute density differences in the early universe that eventually led galaxies to form. The large, diffuse swirling pattern across the sky is the foreground light emitted by dust, churning gas, and energetic particles in our galaxy, the Milky Way, through which we view the universe.

It's tempting to think of the CMB as an afterimage, like a film negative preserved on the outer edge of the universe. Here on Earth, we think in meters and kilometers and feel like we see events as they happen. But even something as fast as light takes time to traverse vast cosmic distances, and our current view reflects what the CMB looked like more than 13.7 billion years ago. It's the actual "light" carried as photons—like little truckloads of energy—finally reaching us after crossing billions of light-years of space. Its large-scale variation is a direct image of the largest and most distant structure of space and time. As such, it tells us a lot about how everything started.

Yet the CMB also poses a puzzle. On the one hand, its pattern faithfully reflects the structure of the universe and offers compelling evidence supporting the Big Bang and the physical theories that we believe govern the cosmos. On the other, as my own research reflects, the CMB that exists is almost ridiculously atypical when compared with all of the CMBs that might have arisen from generic random noise. Understanding what that means, like comprehending the universe itself, requires some perspective.

Einstein and Hubble

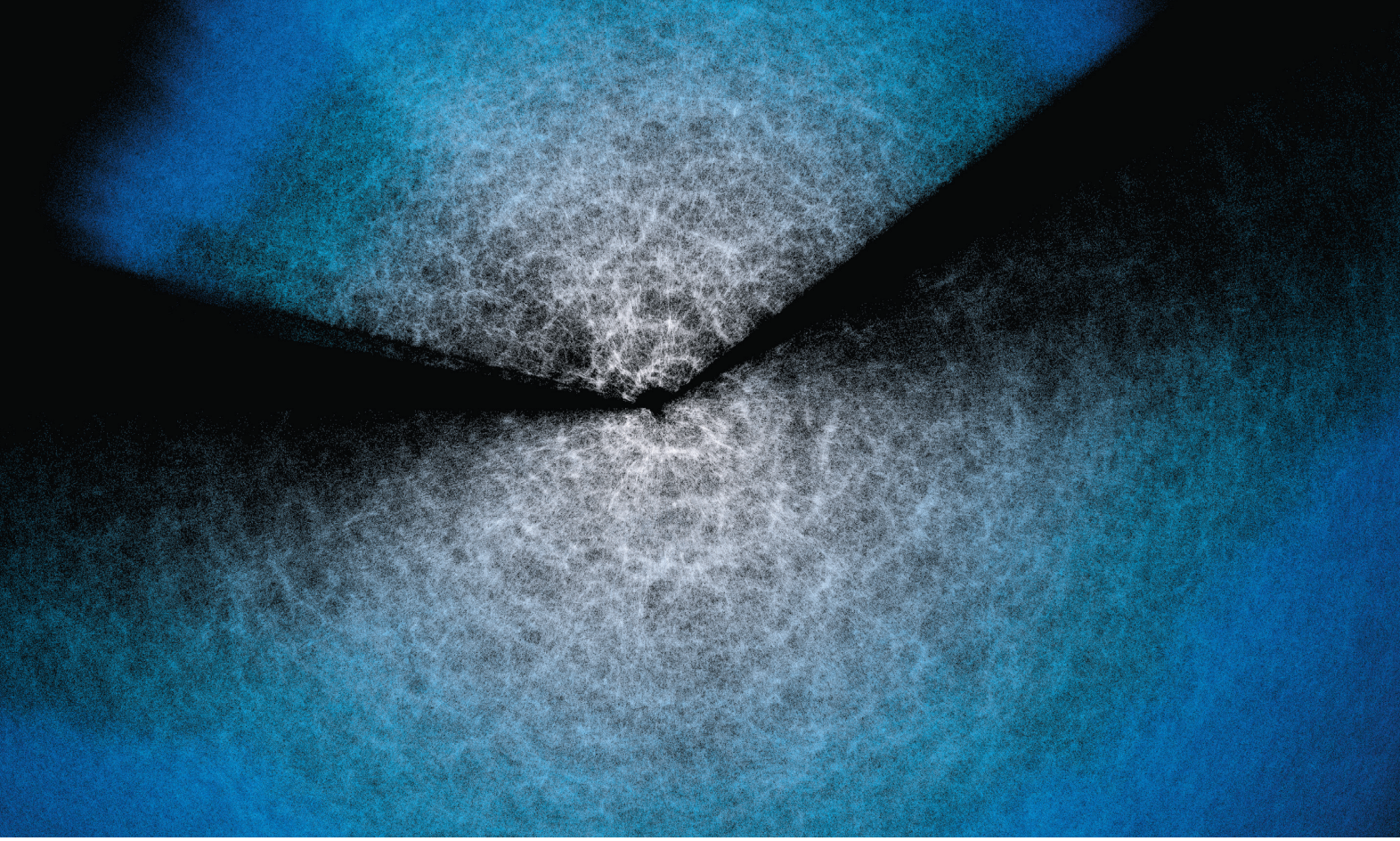
Alfred Einstein's 1905 special theory of relativity showed that light has a constant velocity only because absolute time and absolute position do not exist, and because space and time are not independent of each other. Scientists visualize this interrelationship as a four-dimensional geometry called *space-time*, consisting of three spatial dimensions plus time.

QUICK TAKE

The cosmic microwave background (CMB), relic radiation from 380,000 years after the Big Bang, is our oldest record of temperature and density conditions from the universe's infancy.

Its pattern preserves how quantum fluctuations during the post–Big Bang inflationary period exerted large-scale influences on the cosmic arrangements of galaxies and other matter.

It also poses a puzzle because cosmological and quantum models cannot explain why the CMB is so smooth, except as a fluke. That mystery could suggest the need for new physics.



DESI Collaboration/DOE/KPNO/NOIRLab/NSF/AURA/R. Proctor

This map portrays the cosmic web of galaxies that constitute large-scale structures in the universe, mapped by the U.S. Department of Energy's Dark Energy Spectroscopic Instrument (DESI), the world's most powerful multi-object survey spectrograph. The two observation "fans" show objects further back in time as one moves away from Earth (*center*). DESI shows how the initial conditions, tiny density fluctuations, and physical rules recorded in the cosmic microwave background (CMB) play out as the universe evolves. By combining this data with CMB observations, scientists hope to explain what drives universal expansion and to identify gaps in our understanding of cosmological physics.

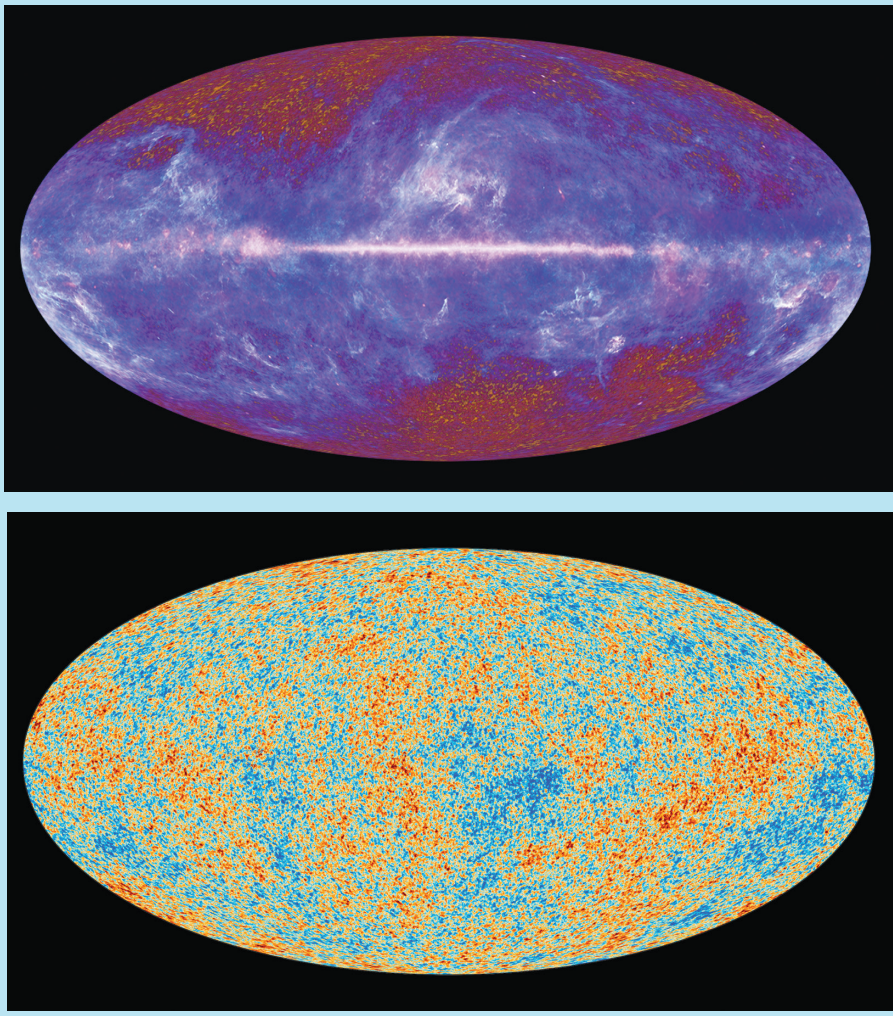
When I compared light photons to cargo on a truck, I was merely providing a useful metaphor for how electromagnetic radiation can take ages to reach us over vast cosmic distances—the fact that we see each star, galaxy, or the CMB itself as it appeared in the past, when light first left that object. Our relationship with time and space everywhere is defined by the light reaching our retina at each instant. We call this particular place and time an *event*.

As shown in the figure on page 358, astrophysicists envision the history of light in space-time as *light cones*, diagrams that portray every past influence that affects an event and every future outcome that an event can influence. The former is represented by a past light cone that narrows until it meets the event in question; the latter forms a future light cone that widens as we move from the event to the future. The cone's sides correspond to light speed (around 300,000 kilometers per second). Since nothing can exceed this universal speed limit, nothing influencing or influenced by the event should lie outside the light cones.

But this picture is incomplete, because it does not include the effects of space-time curvature. To track light's path all the way back to the beginning of time, scientists use a more comprehensive theory: Einstein's 1915 general theory of relativity, which describes how space-time geometry warps and stretches in the presence of matter and energy, creating gravity through curvature. This gravitational curvature changes the trajectory not only of matter, but also of light. The curved geometry of space-time lets us understand how time, space, and gravity behave, and forms the theoretical foundation for unpacking the information preserved in the CMB.

Theorists began using general relativity equations in the 1920s to make mathematical models of possible universe structures, eventually hitting on the now-accepted mathematical framework that underpins the standard model of cosmology: the Friedmann–Lemaître–Robertson–Walker model (FLRW). This complete, highly idealized space-time model teems with matter and energy, has no spatial boundary, and assumes that the universe has the same overall composition and structure everywhere (*homogeneity*) and looks essentially the same everywhere from any given point (*isotropy*). (This latter factor explains why the CMB looks nearly the same in every direction.) In such models, time can have a beginning.

The structure of an FLRW universe is simple: A small volume of the universe, over a limited time, acts almost like empty space-time because of the almost negligible curvature of space (as an analogy, think of how the Earth beneath our feet seems flat, but zooming out to the globe reveals the planet's curvature). But over larger volumes and longer periods, Einstein's field equations tell us that matter and its associated gravity cause a uniform stretching of space-time itself. This stretching depends on the universe's composition (such as matter, radiation, and—following later discoveries that this expansion is accelerating—dark energy) and origins (initial conditions).



ESA/Planck Collaboration

Two full-sky maps reveal the cosmic microwave background (CMB) captured by the European Space Agency's Planck satellite. In the multifrequency image from Planck's first year of data (*top*), our Milky Way galaxy is visible as a bright horizontal line surrounded by a nimbus of gas and dust emissions. The light and dark dots of the CMB that dapple the background become clearer when the foreground is removed in the mission's final data release (*bottom*). Here, false-color encoding shows tiny differences in temperature (a few millionths of a degree) above (red, orange, and yellow) or below (blue) the CMB average (around 2.725 kelvins). These fluctuations correspond to density differences that occurred soon after the Big Bang and that set the underlying pattern for the cosmic structures we observe today—a pattern recorded in the CMB.

Using *comoving distance* and *conformal time*—standardized rulers that expand with space-time and thus "unstretch" it—we can follow the entire history of light and matter back to the beginning. That includes tracing photons from the CMB from the *surface of last scattering*—the time and place where CMB photons last interacted with matter before traveling through space to reach us.

When astronomers like Edwin Hubble began to see far enough into space to glimpse real universal stretching in the distribution and motion of galaxies beyond our Milky Way, they noted that light spectra from such galaxies showed atomic lines that were systematically shifted to longer wavelengths—the red end of the spectrum. Scientists interpreted this *redshift* as an effect of motion away from us, much as a Doppler shift of sound waves stretches the sound of a receding ambulance siren, shifting the pitch downward. By 1929, Hubble possessed enough observations to show that distant galaxies all move away from us at an apparent velocity proportional to their distance. Distant galaxies appear to recede because space-time is itself expanding, and redshift occurs as the wavelengths of galaxies' photons stretch along with space-time.

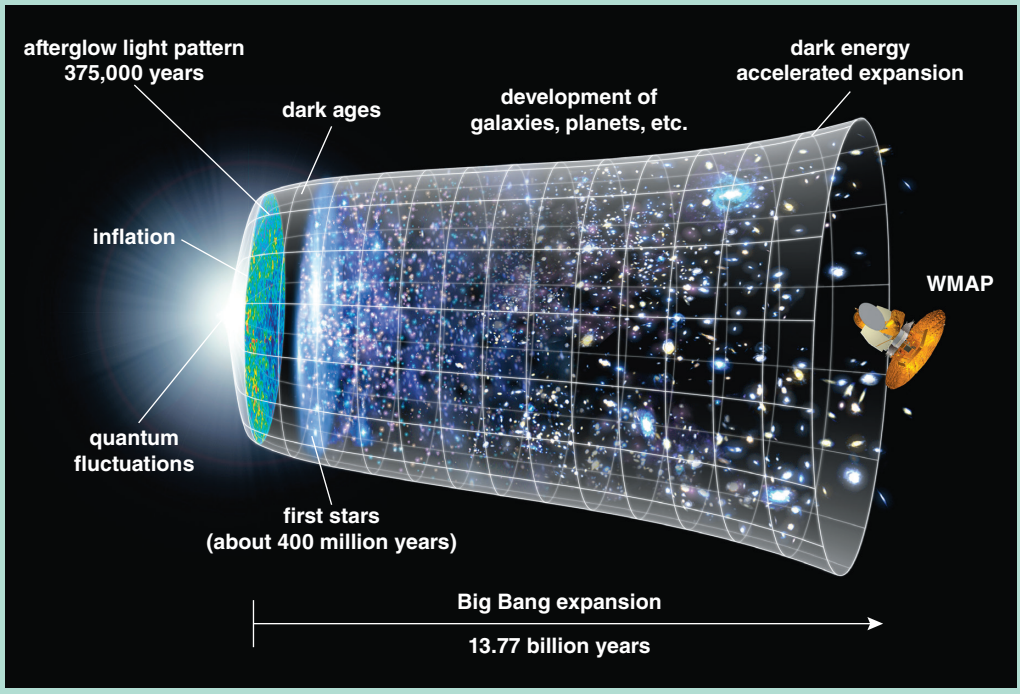
Decoding the CMB requires combining what Einstein said about curvature and relativity, what the FLRW model tells us about space-time geometry, and what Hubble's law tells us about redshift: Any observer viewing more distant galaxies is peering farther into the past, so expanding space has stretched the light of those galaxies to longer wavelengths (hence, over more than 13.7 billion years of time and across more than 45.7 billion light-years of distance, the CMB has redshifted from visible light to millimeter-wavelength light microwaves). Averaged over a very large volume of space, the FLRW model offers a useful way to think about how the universe behaves on large scales.

The Cosmic Microwave Background

The CMB, discovered in 1964 by American astronomers Arno A. Penzias and Robert W. Wilson, marks a time when space was full of energy scattering off matter. In this very early universe, which existed not long after the Big Bang but long before galaxies formed, everything was crammed closer together; space was very dense, very nearly uniform, and very rapidly expanding. Interaction with matter gave radiation during this period a nearly perfect, universal *black-body spectrum*, that is, the kind of spectrum predicted by German physicist Max Planck for what are called black bodies (idealized objects that perfectly absorb radiation).

Planck's law says that the thermal radiation emitted by a black body should move to shorter wavelengths as the body's temperature rises; if it's hot enough, we can even see those emissions. I find it profound that, when COBE in 1991 first made its ultraprecise CMB measurement, the background radiation spectrum from all directions exactly agreed with the mathematical formula postulated by Planck in 1900 based on pure physics. The spectrum today is the same as light (microwaves) radiated by any opaque matter at an absolute temperature of 2.725 kelvins. When the spectrum formed in the early universe, prior to the last scattering and before cosmic expansion cooled it, it glowed many thousands of times hotter and interacted with matter many billions of times denser than today.

This visualization of cosmic expansion shows how the universe's size (represented by the diameter of the "bell") rapidly increased during the inflationary period just after the Big Bang, then gradually slowed as matter pulled on itself via gravity, and later sped up due to dark energy. The cosmic microwave background (CMB, multicolored disk) marks a moment around 380,000 years after the Big Bang when photons could first travel freely through space. Spacecraft such as the Wilkinson Microwave Anisotropy Probe (WMAP, shown here) as well as the Cosmic Background Explorer and the Planck satellite help us view the CMB in detail and potentially understand the quantum fluctuations and density variations that led to our large-scale cosmic structure.



NASA/WMAP Science Team

This elegant measurement and simple interpretation of the CMB spectrum provides clear evidence that the universe, and space-time itself, began with dense matter and radiation—a hot Big Bang. Indeed, the CMB offers one of the chief lines of evidence for the Big Bang.

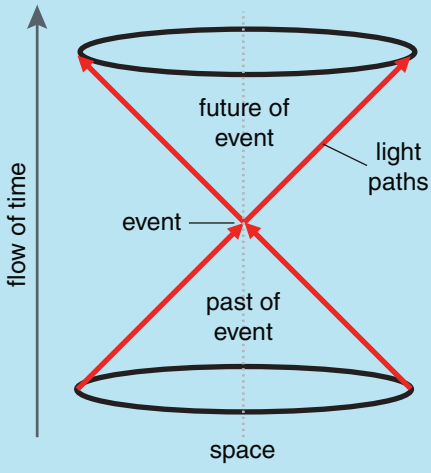
The idealized uniform FLRW universe captures the main global behavior of space and time, but none of the rich structure of the real, non-smooth universe, or any of the wonderful things that have happened within it during billions of years of cosmic evolution. A perfectly smooth universe would have produced no galaxies, stars, or planets, and no people to view them. All those events and structures started out from tiny nonuniformities of initial conditions that also led to *anisotropies*, minuscule temperature fluctuations (a few parts per 100,000), that COBE first measured in 1992. These hot and cold spots reflect density differences in the early universe as it rapidly underwent post–Big-Bang expansion and are associated with gravitational field variations that set the pattern for the unfolding universe. Planck satellite data let us view what variations from a smooth universe look like.

The fine-scale mottled pattern of hot and cold patches in the bottom image on page 356 is shaped mainly by waves of radiation and matter in the early universe, when the radiation was hot enough to ionize matter into a light-scattering plasma not unlike the surface of the Sun. Compression and rarefaction (squeezing and stretching) from initial gravitational variations generated waves in the hot plasma, where radiation (photons) and matter (protons and other nuclei, or *baryons*) were tightly coupled as photons scattered off electrons, which were electromagnetically bound to baryons. These were acoustic waves—pressure oscillations in a medium, just like familiar physical sound waves—but their wavelengths extended hundreds of thousands of light-years. Those waves stopped sloshing around when the universe cooled to about 1,000 times hotter than it is today, at which point the universe turned transparent and radiation could move freely. That is the moment, 380,000 years after the Big Bang, captured by the CMB snapshot. Since then, radiation has traveled freely through space until it reaches us.

This elegant measurement of the CMB spectrum provides clear evidence that the universe began with a hot Big Bang.

Those sloshing radiation–plasma waves at recombination created a distinctive, precisely calculable pattern in the CMB. Scientists can decode the pattern's statistical blotchiness into precise measurements, which experts often portray as an *angular power spectrum*, a function of angular scale on the celestial sphere analogous to the frequency spectrum of sound (*see figure on page 359*). If we visualize the primordial sky's temperature variation pattern as waves on a rough sea, this function shows how wave height varied as a function of the *angular wave number*, the number of waves that fit around the whole sphere. The red data points indicate measured values from Planck satellite maps; the smooth green curve is calculated from a widely accepted concordance model of a universe filled with matter and radiation, which includes all of gravity's effects on light.

The model fits the CMB pattern with remarkable precision over a wide range of angular scales. The simulation is also consistent with other measurements, in-



Craig Hogan

Light cones **are 3D depictions of cosmic cause and effect. The future light cone above an event represents all the event's future interactions, whereas the past light cone below denotes all the influences that led to the event. Because the light paths that make up the sides of the cones (*red arrows*) measure time in units of light speed (the universe's top speed), nothing outside of the cones, past or future, can exchange information with the event in question. The *horizon problem*—the fact that regions of the early universe appear to have interacted even though they are outside each other's light cones—helped to inspire inflation theory, which says those areas were once much closer together and hence within each other's light cones. The cosmic microwave background sits at the edge of our past light cone.**

cluding how galaxies are distributed in the more recent universe. To get all of these factors right, the model includes dark matter (matter that interacts with gravity but not light). It also incorporates dark energy, the term scientists use for an unknown energy that is causing the expansion of space to accelerate. These ingredients underpin the standard model of cosmology, which grew out of the basic FLRW model and which cosmologists denote as ΛCDM (for dark energy [Λ], cold dark matter [CDM], ordinary matter, and radiation). The success of ΛCDM, especially its precise agreement with CMB maps, as well as its broad agreement with the modern-day galaxy distribution, shows that we mostly understand how cosmic structure on large scales has evolved, almost all the way back to the beginning.

Large-Scale Smoothness of the CMB

The factors that dominate CMB structure depend on the scale under consideration. On scales larger than a few degrees in angle, or bigger than a few hundred million light-years in comoving size (but still much smaller than the observable universe), the initial tiny variations in the distribution of matter and gravity remain mostly unchanged by the sloshing of the primordial plasma (early plasma acoustic waves), so gravity alone has controlled evolution ever since the beginning. That means that, on angular scales larger than a few degrees, the pattern of gravitational variations from initial conditions persists in the form we see today. Apart from the enormous stretching of space, the distribution of CMB temperature on very large scales therefore represents a direct image of the universe's initial state.

As to what the observed CMB tells us about the Big Bang, our models are limited by our access to only one observable universe, the pattern of which was seeded by random processes that occurred during *inflation*—the period of extremely rapid expansion just after the Big Bang, during which the universe grew a hundred billion trillion times bigger in a fraction of an eyeblink. In the standard concordance model, different realizations of random noise in initial gravitational perturbations predict different patterns of CMB anisotropy, which produces uncertainty in any particular sky's predicted spectrum. This theoretical uncertainty, called cosmic variance, appears in the plot on page 359 as error bars and as the fattening green theory curve at small angular wave number values. The angular spectrum plotted in this figure represents only one way to decode the pattern of hot and cold spots in CMB maps.

Alternatively, we can look at the same information using an *angular correlation function*. This function captures how much variation exists on different angular sizes—how rough or smooth the sky looks when averaged on different scales (larger angles cover larger patches of sky). We're interested in this function because we can use it to test our cosmological models, which predict that certain amounts of roughness are consistent with the universe we see. We calculate the angular correlation function by first picking every pair of points in the CMB that lie a certain angular distance apart. After subtracting the temperature at each point from the mean CMB temperature, we multiply the resulting pair of difference values. The average of all those pairwise products is the angular correlation function. If temperatures in all directions were independent of each other, the function would equal zero, because all the positive and negative values would cancel out (except at an angle of 0 degrees, which simply describes two points occupying the same space). The angular correlation function shows geometrical relationships in the universe's initial conditions that are not obvious from the angular spectrum, even though both contain the same mathematical information.

And, as shown in the figure on page 360, that information holds some surprises, particularly when compared with what the standard models predicted should have arisen from the smaller scale variations (which scientists typically model as random noise). Even in the COBE satellite's first measurements, scientists found that correlations of CMB temperature at large angular separation were much smaller than they would typically expect from extrapolating the random noise from smaller scales in the degree-scale mottled pattern. In brief, compared with standard noise models, the universe seems too uniform on the very largest scales. If we occupy a random universe that arose from random noise, we should expect

The waves moved matter up to the maximum distance traveled in the time available, about 500 million comoving light-years, which provides a kind of standard ruler for comparison.

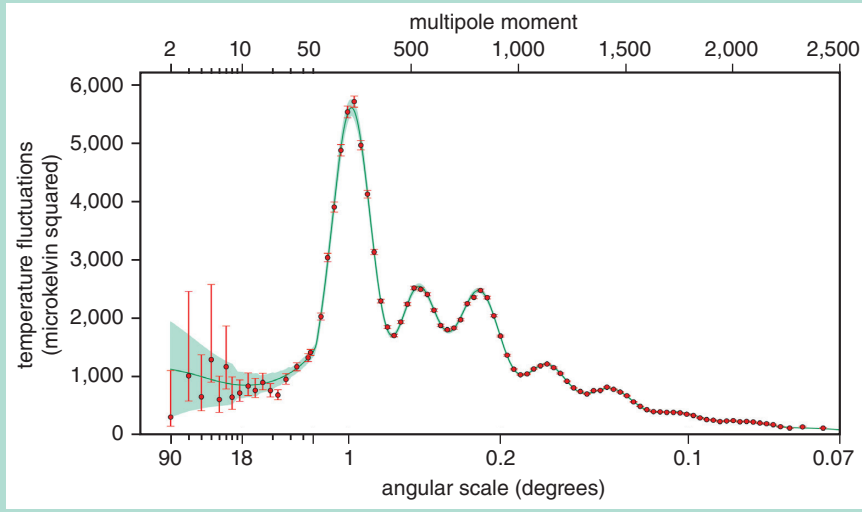
to see all kinds of messy patterns preserved in the CMB. Instead, we observe a neat, uniform pattern that seems extremely unlikely, statistically speaking. So, either we got extraordinarily lucky, or there is some process that requires that the universe be this way.

As later observations by WMAP and the Planck satellite provided more precise measurements, the measured correlation decreased even further. Standard models allow such a smooth universe, but only in extremely rare cases; as better maps were produced, the situation appeared increasingly improbable. Understandably, some half-jokingly call such smoothness a conspiracy, or perhaps a miracle, in the initial conditions. This so-called anomaly has led some cosmologists to suspect that the usual models of primordial random noise may not be completely correct.

Recently, my colleagues and I found that correlation functions of Planck maps at angular separations of around 90 degrees, plus or minus 15 degrees (that is, 75 to 105 degrees), fall even closer to zero than scientists had previously documented. For this measurement, we used the *even-parity* part of the correlation function, which is independent of our motion through the universe. In this angular range, the sky's uniformity is truly remarkable. The standard simulations of randomly generated skies are much farther from zero than the actual maps in the angular separation range of 75 to 105 degrees. In brief, fewer than about one in a thousand random realizations stay as close to zero as the real sky.

Another way to think about the universe's remarkable isotropy on large scales entails considering the average temperature of the CMB, around 2.7 kelvins. The typical variations—the mottled pattern of the CMB—are fractionally tiny, a few parts in a hundred thousand of that value; averaged over the very largest scales, they are even smaller. At nearly right-angle separations (around 90 degrees), the angular correlation function has currently measured values around 1 microkelvin squared.

In other words, average variations from the perfectly uniform average temperature measure at most a few parts in 10 million. Geometrically, the universe on these large angular scales is fractionally about as smooth as the polished mirrors of a high-quality telescope. This remarkable smoothness could point to some underlying uniformity in the universe's initial conditions that require new physics to explain.



European Space Agency and the Planck Collaboration

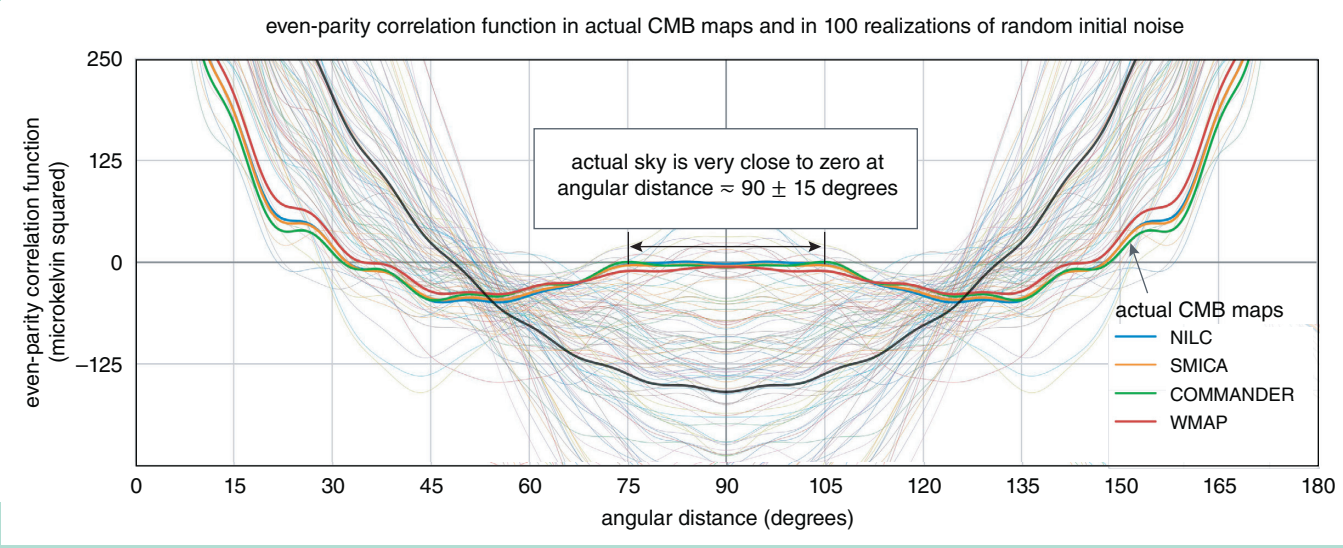
The power spectrum of the temperature fluctuations in the cosmic microwave background (CMB) reveals a key pattern—a measure of the "bumpiness" of temperature fluctuations across the CMB. The graph also shows how well or poorly Planck satellite measurements (*red dots*) agree with predictions made by the widely accepted concordance model of a universe filled with matter, radiation, dark energy, and dark matter. At small *angular scales* (distances between data points measured by the angular portion of the sky separating them), agreement between observations and models remains high. But when angles grow large (*green shaded area*), observed fluctuations are smaller than the ranges predicted by models (*red error bars*), a phenomenon called cosmic variance. Such graphs show how the CMB can help scientists test the validity of cosmological models and find areas that call for improvement.

Primordial Quantum Origins

The large-angle properties of the primordial pattern carry information about things that happened before the beginning of standard classical cosmology—and far past the frontier of familiar physics. Exploring the possibilities contained in those pre-CMB conditions involves extraordinary extrapolations, far beyond conditions observed in nature or studied in the laboratory.

Initial conditions that produced today's large-scale structure arose when all that we now see may have been compressed into a volume smaller than an atom. Generally, experts in my field think that cosmic initial conditions were shaped not just by relativity, but also by the quantum physics that govern elementary particles and fields. They also think that the noise in the initial conditions stemmed from quantum fluctuations of gravity such as occur in matter and light on subatomic scales. Theories of this process not only extrapolate the behavior of matter and energy far beyond tested conditions, they also venture into territory where we do not even know for sure what basic principles governed space and time. When our reasoning stretches known physics to the borderlands of conjecture, we shouldn't be surprised if we encounter some surprises.

The peaks and valleys in the angular spectrum represent a distinctive imprint on the sky from the spectrum of sloshing waves in primordial plasma.



From Hogan, 2025

This angular correlation shows aspects of the universe's initial geometry and conditions that are not obvious from the angular spectrum graph, even though both graphs contain the same data. This plot compares the angular distance in degrees between two points in the cosmic microwave background (CMB) (*x-axis*) with a function that shows how closely correlated those two points are (*y-axis*). Negative values have opposite temperatures, positive values have similar temperatures, and zero indicates no correlation. Bold lines show actual CMB maps processed with various algorithms: NILC, SMICA, COMMANDER, and WMAP. Fainter lines are plots from 100 simulated "random skies" generated according to the standard inflationary model as a baseline for comparison. Curiously, the CMB data for our universe falls far closer to zero than almost any predicted outcomes, which suggests the need for new theoretical insights.

Quantum physics describes the basic rules for how all forms of energy and matter behave, but theorists still have not fully reconciled quantum physics with general relativity, the basic rules that describe how space and time behave. In the universe studied by physicists today, these two worldviews are separated by scale (gravity is negligible on atomic scales). Inconveniently, this theoretical gap means that no experiments currently provide clues as to how nature combines gravity and quantum behavior into one all-encompassing set of rules. Cosmological initial conditions are the only place where both quantum and gravitational dynamics interact significantly—an interplay that created the primordial gravitational noise visible in the CMB anisotropy. The fact that scientists cannot use well understood physics to make a complete theory of this noise is actually good news, because it suggests that the CMB pattern could reveal new fundamental physics and symmetries we cannot study any other way.

We try to understand cosmological initial conditions by extrapolating certain elements drawn from relativity and quantum theory and calculating what they predict. In one widely studied family of inflationary models (models in which the cosmic expansion rapidly accelerated during the first tiny fraction of a second), scientists posit the existence of a new set of exotic quantum energy fields beyond those already found in nature (such as electromagnetism) whose exotic energy drove accelerated expansion. They also assume that the gravity of these fields followed some of the same basic quantum rules as extant matter and energy fields, so that their quantum fluctuations directly map onto spatial variations of space-time curvature.

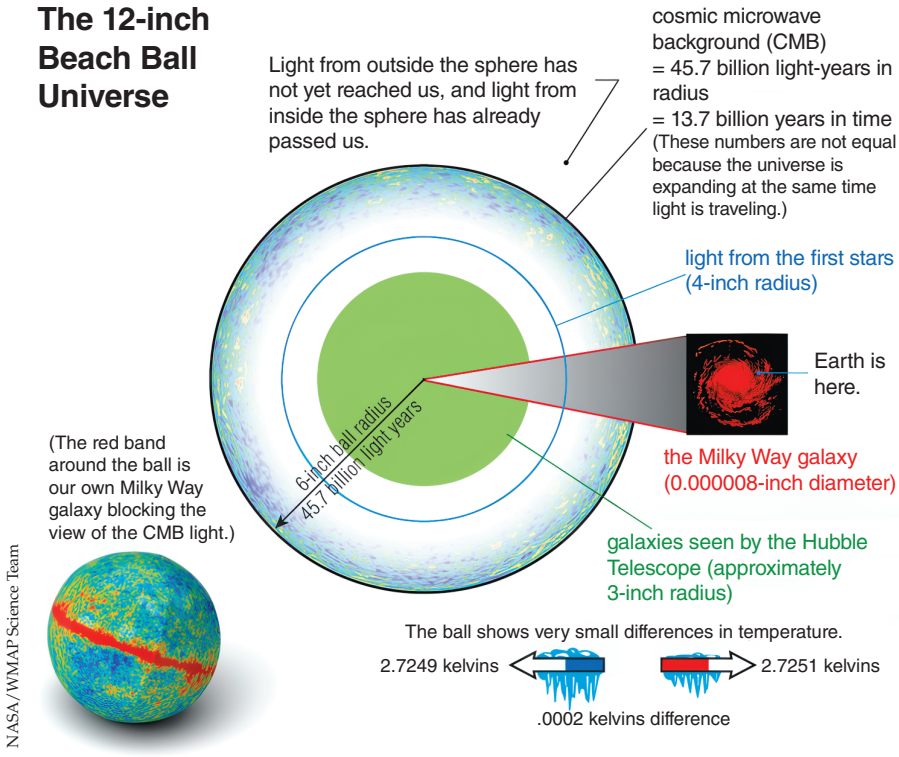
With the right kinds of fields acting on an initially uniform patch of FLRW space-time, the gravity of early-era exotic fields makes the *scale factor* (how the universe's size changes over time) accelerate, growing exponentially as the expansion of inflation accelerated. During this era, the stretched conformal time extends back to negative values. The "zero hour" of conformal time correlates to the end of inflation, and negative values take us back through the inflationary period "before the beginning" of time in the original FLRW models. During this early era of rapid inflation, any location's causal past, or *horizon*, extends to larger comoving regions the farther back we go, so microscopic quantum processes could possibly have made cosmic structures we see on large comoving scales today.

With the right assumptions about the initial vacuum state (a configuration with only the minimal excitations expected from quantum uncertainty) and the quantum coherence of the new fields that dominated the universe during this period, the widely adopted inflationary models end up producing a universe with random noise like that assumed by the concordance cosmological model that fits the CMB's degree-scale pattern so well.

In this framework, that pattern on large scales is a kind of fossil record preserving the early universe's quantum fluctuations. Studying this record in the context of inflationary models links quantum physics (the physics of the very small) to structures on cosmological scales. Moreover, whereas quantum inflation models statistically explain the CMB's "random" patterns, the CMB's angular power spectrum lets cosmologists evaluate predictions made by inflationary models.

Quantum Lessons: Cosmic Structure

Although inflation excels at explaining much of what we observe, especially in the CMB, scientists have questioned some of the idea's underlying assumptions ever since American theoretical physicist Alan Guth pioneered the idea more than 40 years ago. For example,



A 12-inch beach ball can provide some perspective regarding the scale of the expanding universe and the nature of light. If we imagine ourselves at the center, the ball's 6-inch radius represents the distance light has traveled over the more than 13.7 billion years since the universe cooled enough to allow light to travel freely. The cosmic microwave background would be as far away as the inside surface of the ball—far older and more distant than the first stars and galaxies.

inflation does not at all explain the most significant symmetries: the origin of the perfectly unperturbed classical background patch of FLRW space-time that theorists assume the fields start on, or how to prepare the initial quantum vacuum state across that patch.

On a more basic level, since it does not address many basic inconsistencies between gravity with quantum mechanics, the standard inflation model could lack critical physical elements regarding how quantum fluctuations of gravity really work. A better, more complete theory could still incorporate known basic principles of causality and quantum mechanics, but with elements of quantum mechanics extrapolated in a different way to gravity.

For example, physicist Roger Penrose of the University of Oxford has argued eloquently that initial conditions must depend on fundamental symmetries beyond those of standard inflation theory and should incorporate what we have inferred about gravitational *quanta* (tiny parcels of energy) from the theory of black holes, objects with gravitational fields so strong that not even light can escape. Penrose has proposed that a new, fundamental geometrical symmetry of initial conditions explains the ultimate origin of extreme cosmic uniformity on the largest scales and even explains the global difference between the past and future—the "arrow of time" defined by the increase in thermodynamic entropy in systems throughout the universe.

The measurement made by me and my coauthors of near-zero correlation in real CMB data from WMAP and Planck supports such skepticism about some basic assumptions that go into quantum fluctuations of standard inflation models. The issue is not inflation itself, but rather that the quantum model of the standard type cannot explain the uniformity we see in the actual sky and can only attribute it to a very unlikely chance. Possibly the negligible angular correlation measured in the CMB at angles of around 75 to 105 degrees does not indicate a statistical stroke of luck but rather hints at new physics; perhaps it's a relic of a deeper fundamental symmetry in the four dimensions of quantum–gravity fluctuations prior to the beginning of classical time. Such symmetry could emerge if gravitational fluctuations have correlations that are causal but nonlocal, existing between distant points in space-time, not unlike the entangled quantum systems of matter and light that physicists now extensively study, but which Einstein once dismissively labeled as "spooky."

A hundred years ago, experimental results forced scientists to accept a new and strange quantum world. We might now find that cosmological data could guide theory into uncharted territory, where quantum weirdness shapes the force of gravity. New CMB surveys now underway will probe more deeply into the inflationary era. They seek another proposed direct signature of quantum gravity, a distinctive pattern of CMB polarization correlations that could be generated by stretched primordial quanta of gravitational radiation. Whether or not they find this effect, these surveys will better enable astronomers to produce a clearer, less obstructed view of the universe's initial state. The microwave image spread across the sky already provides the clinching evidence that we live in an expanding universe born of a hot Big Bang. The next round of studies may start to reveal why and how it went "bang."

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▶ This essay is adapted from a version published on Aeon (aeon.co).

Rethinking Adult ADHD

The diagnostic category for attention-deficit/hyperactivity disorder has become more inclusive, but that does not mean the condition is being overdiagnosed.

Margaret Sibley

In late 2023, while taking a break at a conference in Baltimore, I shared a *New York Times* chart, based on detailed census records, with a colleague from the U.S. Centers for Disease Control and Prevention (CDC). The data showed a sharp rise since 2020 in Americans reporting serious difficulty remembering, concentrating, or making decisions, which are among the symptoms of attention-deficit/hyperactivity disorder (ADHD). Moments earlier, my colleague had presented a graph with a nearly identical curve—this one tracking the steep increase in adult stimulant prescriptions since 2020. By 2023, CDC data had confirmed that a record 7.8 percent of American adults reported an ADHD diagnosis. Google searches for "ADHD" had surged, and TikTok videos tagged #ADHD had racked up more than 20 billion views. At the very most, we were experiencing an adult ADHD epidemic in the United States. At the very least, ADHD was now suddenly very fashionable to the public. Yet, a third explanation is also possible: For better or worse, the ADHD diagnostic category might be becoming more inclusive.

Let's examine the possibility of an adult ADHD epidemic. This option would be possible only if adult-onset ADHD were a valid phenomenon. ADHD is classified as a neurodevelopmental disorder in the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM*), a handbook published by the American Psychiatric Association to govern responsible diagnoses of mental disorders by health care practitioners. The neurodevelopmental disorder category (which also includes intellectual disability and autism spectrum disorder) is characterized by disrupted brain functioning stemming from abnormal neural development. ADHD is largely inherited through a person's genes, but it is also influenced by environmental factors such as stressors and protective supports. As the *DSM* defines neurodevelopmental disorders, onset is in childhood, but the course usually lasts a lifetime. In the case of ADHD, the *DSM* requires onset of at least some symptoms—difficulties in self-regulation such as attention problems, hyperactivity, mental restlessness, and impulsivity—by age 12.

Consistent with the *DSM*'s description, research suggests that ADHD is a chronic and lifelong experience for most with the diagnosis. Studies investigating the possibility of true adult-onset ADHD have largely come up empty-handed. So, what explains rising rates of adult ADHD in the United States over the past five years?

One factor may be that the *DSM* has become more inclusive. In 2013, the *DSM* was revised to its fifth edition with several changes that formally relaxed ADHD's diagnostic criteria; however, it is unclear what effect these changes had on future diagnostic rates. *DSM-5* pushed the cutoff for the age of onset from 7 to 12 years old, reduced the number of symptoms needed (from six to five) for an adult ADHD diagnosis, loosened the level of impairment (problems in daily life functioning) required for diagnosis, and allowed individuals with autism spectrum disorder to receive a co-occurring ADHD diagnosis. Ultimately, by expanding the diagnostic category, these changes may have increased rates of ADHD diagnoses in adults and children. The *DSM* revision happened in 2013, so it seems unlikely to have triggered the sudden spike in adult ADHD diagnoses in the 2020s. Still, relaxing the adult ADHD criteria may have been one source of kindling for that later explosive trend.

Although the *DSM-5* portrays ADHD as a disorder you either have or have not, that characterization is a false binary. Indeed, the diagnosis of ADHD demonstrates a condition that represents the extreme end of a trait continuum, similar to the range of severity in conditions such as hypertension and obesity.

Health care providers often use a checklist of behaviors which, in aggregate, form a person's level of *trait ADHD*. Everyone falls somewhere on this continuum, which includes a person's abilities in areas such as paying attention, organizing tasks, remembering daily activities, and modulating their verbal and motor activity levels.

QUICK TAKE

Adult ADHD diagnoses have become more common as the definition of the condition has broadened. However, treatment of "light ADHD" does not constitute overdiagnosis.

Social media posts have spread awareness about ADHD symptoms. Unfortunately, the quality of this online content varies, and some users promote questionable treatments.

The neurodiversity movement has helped some patients embrace their ADHD diagnosis. ADHD, like other neurodiverse conditions, has a spectrum of symptoms and severity.

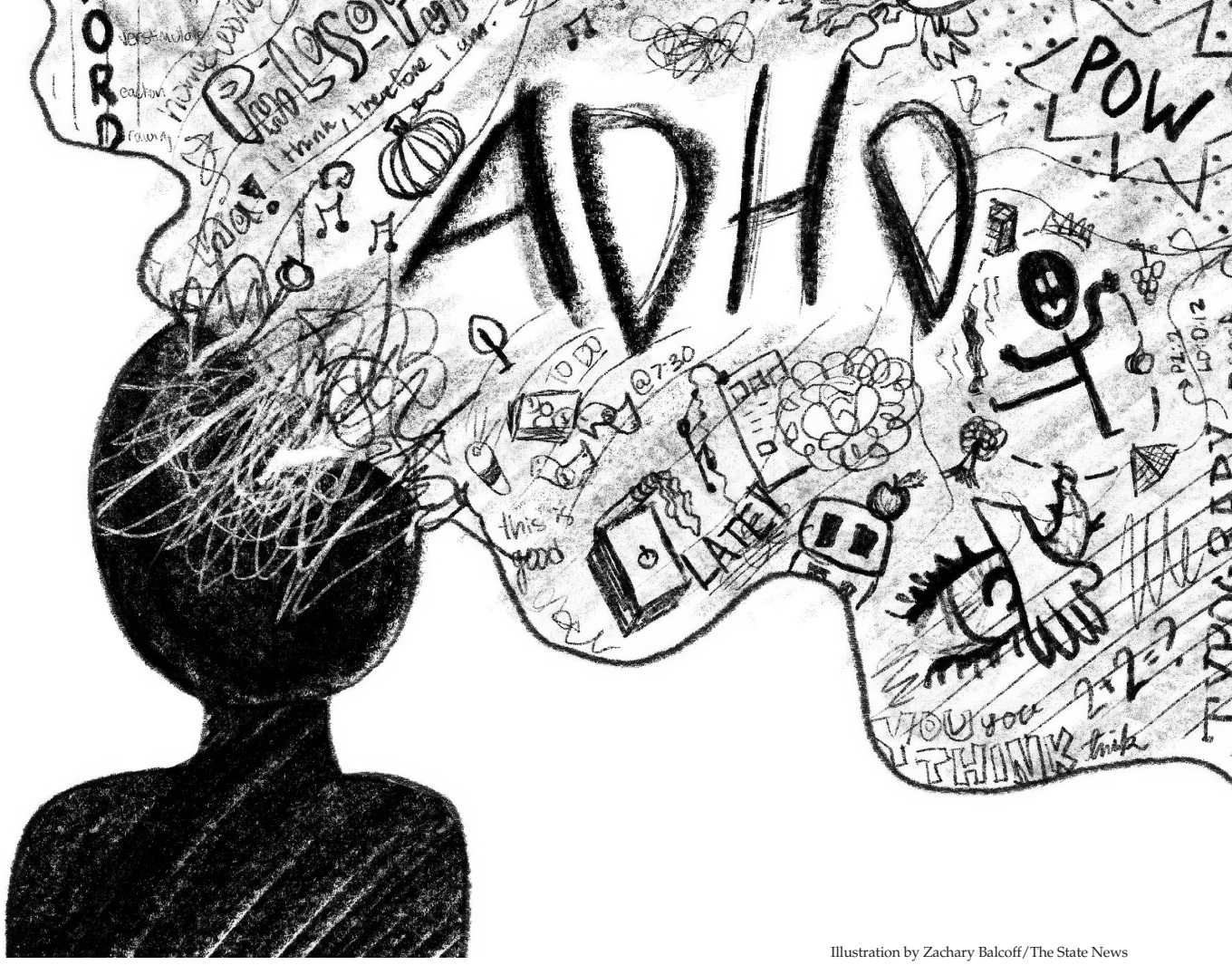


Illustration by Zachary Balcoff/The State News

An increasing number of U.S. adults are being diagnosed with attention-deficit/hyperactivity disorder (ADHD), which has led some researchers to speculate about overdiagnosis. However, the spike in cases is more likely due to broadening criteria for the disorder and increasing awareness of the symptoms through social media trends.

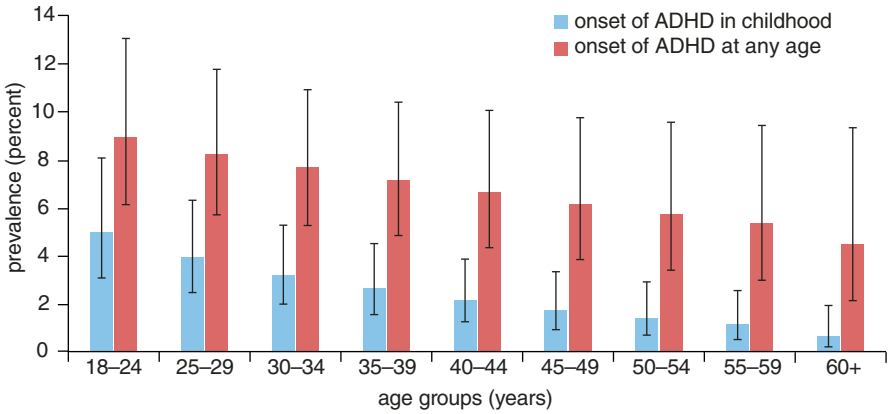
People with very low trait ADHD do very well with most of the behaviors on the checklist. People with high trait ADHD will struggle with many of them. If a person describes above average ability on the checklist, we call it a strength. When someone has below average ability, we call it a weakness or a symptom.

Trait ADHD displays a bell curve in the U.S. population, and providers must decide where to draw the line between weakness and clinical diagnosis. Formally, the *DSM-5* offers a symptom cutoff for adults—at least five of nine formal symptoms of either inattention or hyperactivity/impulsivity. But ADHD symptoms are common and relatable—in fact, the average U.S. adult experiences two to three. How severe of an impairment is enough to deem a symptom as present? Conventional clinical wisdom advises that when a person can't manage everyday life because of prominent and chronic ADHD symptoms, an ADHD diagnosis is appropriate. Yet, inevitably, clinicians encounter a gray area when individuals present with mild ADHD weaknesses and no obvious struggles in daily functioning.

An ADHD Spectrum

Making an adult ADHD diagnosis can be done with confidence in someone like Jake, a 26-year-old I first met when he was a visibly hyperactive third grader. (Names and key identifying details have been changed throughout this article to protect patient confidentiality.) If Jake walked into a mental health clinic seeking evaluation for adult ADHD, he could share clear stories from his childhood as an athletic but severely bullied child who received help at school due to disabling problems focusing and completing schoolwork. His highly invested parents could corroborate Jake's account with their own struggles wrestling with him over personal hygiene and sacrificing their free time to provide Jake the academic support needed to cross the high school finish line. Now in his mid-20s and still living at home, he appears friendless, withdrawn, and immersed in video games. Although it took him six years, he completed a bachelor's degree in education, hoping to become a teacher. But with inconsistent motivation to engage in an employment search and challenges with social interactions, he has been working at the local zoo's ticket counter. Since Jake does not have a car (he crashed the last two and could not afford a new one), his father drops him off each morning on his way to work.

Jake's impairments due to his ADHD would be obvious to a clinician. He has experienced many negative consequences because of chronic, elevated trait ADHD, and these consequences reduce and interfere with his daily life functioning. Like Jake, adults with ADHD experience a range of consequences that can include employment instability, educational under-attainment, strained relation-



S. V. Faraone, et al. 2024.

ADHD becomes less prevalent as people grow older, but the disorder occurs in adults of all ages, regardless of whether they were diagnosed with the condition as children.

ships with family members, limited social relationships, driving and safety incidents, and challenges managing a household. They also can experience hidden psychological impairments with self-esteem, stress response, anxiety, self-doubt, and feeling disconnected from others.

Increasingly, health care providers are meeting with patients who experience a lighter form of ADHD. When Rebecca walked into a clinic for a possible first-time ADHD diagnosis, she was 41 years old. It had not occurred to her that she might have ADHD until Facebook ads started popping up on her feed during the COVID-19 pandemic. One said: "Working hard but not moving up? You might have undiagnosed ADHD." Another said: "Indecisive? Anxious? A two-minute quiz can tell you if you have ADHD." One day, her curiosity got the better of her, and she clicked on an image. Looking back on the past 20-plus years of her adult life, she wondered whether a diagnosis of ADHD would explain some of the struggles and disappointments she had experienced.

Most notable to Rebecca was her lack of success in the dating department. Sure, she had a serious boyfriend of four years who was a great, laid-back guy. He owned the house they lived in together and had a successful job. He was eight years younger and, like her, saw the prospect of children as a ball and chain to be avoided. Prior to this relationship, though, she had been devastated by two broken-off engagements and one long-term partnership in which she had been cheated on for years. Her entire social circle had known it was happening, but no one had said anything. Rebecca processed these experiences as personal failures that were her fault, though she could not quite explain what she had done wrong. She had many close friends and was gifted at several hobbies, including surfing and pottery—her pieces showed in local galleries and were a dependable income source. Nonetheless, Rebecca felt that she was not the full package.

It was not just intimate relationships that had been a source of emotional pain for Rebecca. Although she had graduated with honors from a top-notch college studying industrial design, she had bounced between jobs over the years, chronically indecisive about whether she preferred to work for herself or someone else. As a talented jack-of-all-trades, she could easily pick up work in several different arenas, but ultimately found these endeavors curtailed by the temptation to take off to work and travel abroad for months. Now, in midlife, she was questioning the life decisions that had left her living paycheck to paycheck, with no savings or assets.

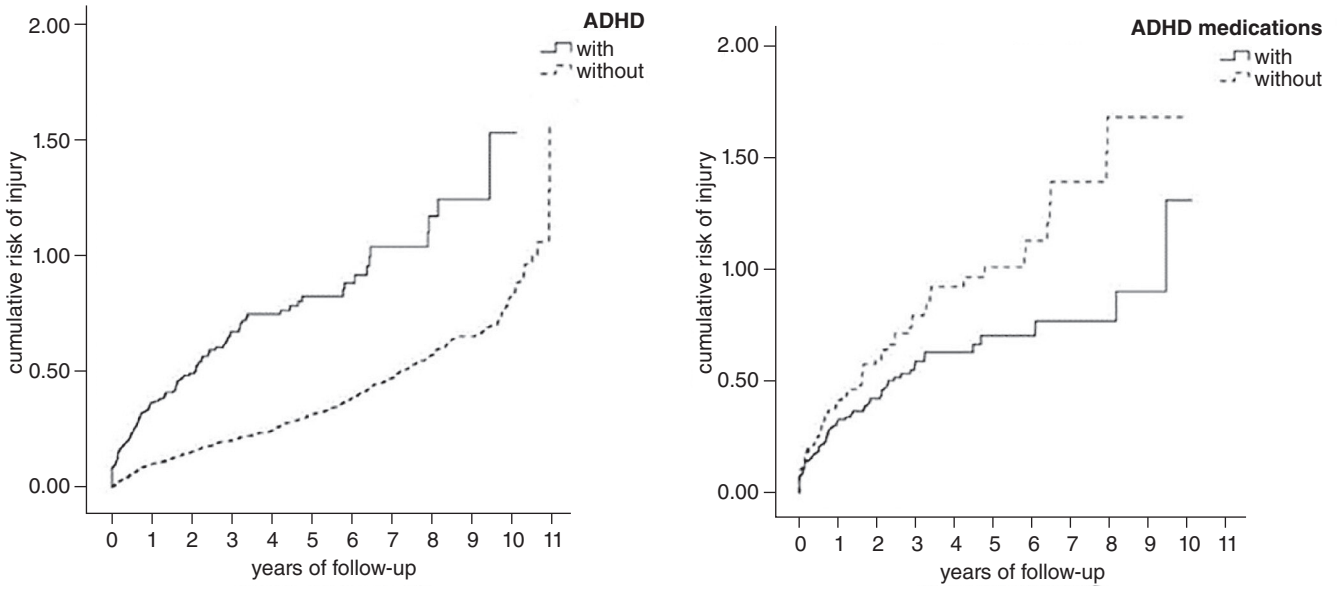
Rebecca would be a much more challenging diagnostic scenario for clinicians than Jake. With no obvious childhood history of ADHD symptoms, some might dismiss the possibility of ADHD immediately. Yet Rebecca reports a moderate amount of relationship and employment instability, as well as financial impacts of her life decisions, paired with persistent feelings of self-blame and self-doubt. These negative experiences can be linked to a pattern of restlessness (a form of mental hyperactivity) in her life, but she reports only three symptoms of inattention and two symptoms of hyperactivity or impulsivity on an ADHD checklist—not enough for a diagnosis. Rebecca's clinician might feel stuck on whether to make this borderline diagnosis of ADHD. Yet, after performing the due diligence of interviewing her boyfriend, Rebecca's clinician becomes a bit more confident. Her boyfriend describes forgetfulness, difficulties with follow-through on household tasks, talkativeness, and distractibility as just "a part of who she is."

Ultimately, the clinician evaluating Rebecca returns to the question of whether her symptoms are interfering with her functioning and decides to make the diagnosis. But, just as easily, another clinician might have dismissed Rebecca's "ADHD-light" as *subclinical* (not severe enough for diagnosis), noting that the symptoms are not substantially interfering with her daily life and that her childhood history of ADHD is inconclusive.

Many, like Rebecca, sit in a gray area of the ADHD bell curve.

Before dismissing Rebecca's ADHD entirely, let's consider the defensible argument for treating adults with light or subclinical ADHD. Many subclinical adults go on to experience full ADHD at another point in their

Compared with the general population, adults with subclinical ADHD are at elevated risk for secondary complications from their symptoms, such as substance use disorders.



A. R. Kosheleff, et al. 2023; graphic reprinted with permission from W. C. Chien, et al. 2017. *Research in Developmental Disabilities.*

Living with ADHD is not just about a short attention span; people with ADHD frequently experience social, educational, and professional impairments. They are also more likely to engage in risky behavior, which may in part explain why adults with ADHD are more likely to become injured than those without the condition (*left*). Medication can mitigate many ADHD symptoms, including risk of injury (*right*).

lives—so helping Rebecca now (with an evidence-based approach such as cognitive behavioral therapy or a low dose of medication) could be viewed as a form of prevention.

Research suggests that subclinical ADHD is not always associated with ADHD's signature cognitive differences such as executive function difficulties, and it is less likely to be associated with a family history of the disorder. Individuals with subclinical ADHD often do not experience meaningful impairments or co-occurring diagnoses and are more likely to notice benefits such as creativity from their ADHD than people with moderate to severe ADHD. Yet, compared with the general population, they are at elevated risk for secondary complications from their ADHD symptoms, such as substance use disorders. They also appear to respond to treatment in similar ways to individuals meeting full ADHD criteria. So, if Rebecca's provider thought she could benefit from treatment, they might make the diagnosis to qualify her for care.

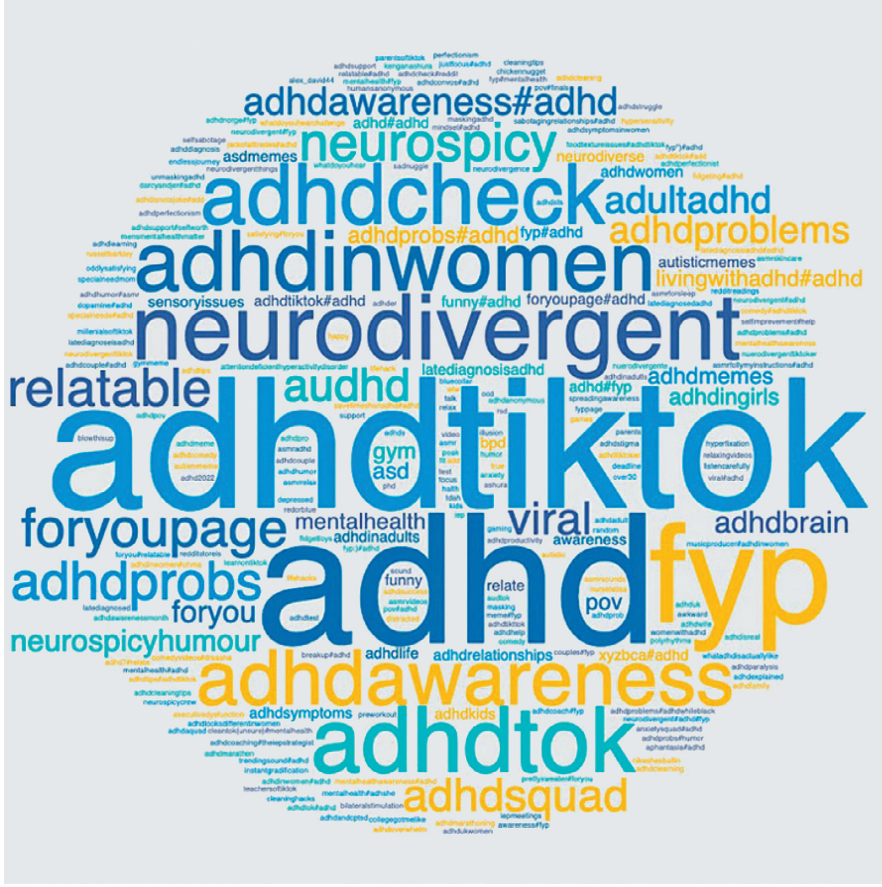
Embracing Neurodivergence

One factor that may be nudging subthreshold and mild ADHD patients such as Rebecca into clinics is the emerging neurodiversity movement. Diagnosed with ADHD, Rebecca feels she is seeing her life clearly for the first time and experiences meaningful relief with treatment. This transformational experience, felt by many late-diagnosed ADHD-light adults, is calling into question the rigidity of ADHD's diagnostic requirements. The argument is that people like Rebecca—who might not meet ADHD's traditional impairment and childhood-onset criteria—should not be denied the opportunity to hold a diagnosis that feels true to their identity and resonates with their lived experiences. This framing is part and parcel of the neurodiversity movement, whose ideas caught fire in the ADHD community during the COVID-19 pandemic. The neurodiversity framework encourages a more inclusive definition of adult ADHD as a fundamentally disabling neurotype, regardless of one's external impairment level.

The transformational experience felt by many late-diagnosed "ADHD-light" adults is calling into question the rigidity of ADHD's diagnostic requirements.

A clinician adhering to the neurodiversity conceptualization of ADHD might consider the concepts of *masking* (camouflaging ADHD symptoms to assimilate to social norms) and *compensating* (employing strategies that mitigate the impact of symptoms on daily life) when forming diagnostic conclusions. Ultimately, the clinician might override the need to demonstrate objective impairment or childhood symptoms if they can point to identifiable masking or compensatory factors that prevented the emergence of those symptoms. The neurodiversity movement also raises questions about whether the exhaustion from constantly suppressing one's ADHD can supplant the impairment criterion. Interestingly, many common mental disorders in the *DSM-5* have a "distress and/or impairment" criterion for establishing clinically sufficient severity, but ADHD employs only an impairment criterion.

Rebecca's clinician might point to her intelligence and sought-after talents as strengths that masked her



V. Karasavva, et al. 2025.

The recent increase in adult ADHD diagnoses correlates with a rise in social media content from adults living with the condition. The 100 most-watched TikTok videos with the hashtag #ADHD on January 10, 2023, used related tags to increase their visibility, as illustrated in this word cloud. The social media posts ranged in quality, from research-backed information to offers of dubious treatments.

childhood symptoms and allowed her to compensate for ADHD as an adult. If she had not been so good at school and so charismatic in her personality, perhaps ADHD traits would have visibly emerged in childhood. If she had not had multiple monetizable skills, and a boyfriend providing free housing, her prominent restlessness could have become a serious threat to her financial survival. Even Jake found ways to offset his ADHD with help from his parents—what would his life be like today if they had not pushed him through his education, given him a stable place to live, and provided him with reliable transportation? Still, if a person is a sum of their parts, then it's also defensible to take a holistic view of ADHD—that Rebecca is a person whose net impairment level is not that meaningful.

The ADHD women's movement is mobilizing around the sentiment that women with ADHD were missed en masse during childhood due to diagnostic criteria that favor men and boys.

Several pandemic-related factors may have also contributed to the tug-of-war over ADHD's diagnostic borders. As people began to spend more time online during lockdowns, many people increasingly shared their diverse lived experiences with ADHD. An explosion of ADHD anecdotes shared on social media may or may not have aligned with scientifically validated information about the disorder, but they certainly stretched the public's conceptualization of ADHD's many faces. Because novel rather than tried-and-true information garners the most social media clicks, a long list of "secret" or "unrecognized" crowdsourced ADHD symptoms began to proliferate online. As this list grew, so did the number of people who found the ADHD diagnosis to be relatable.

The rise of the #ADHD world also created some moneymaking opportunities. Many ADHD posts touting lived experience linked directly to purchasable products or services such as supplements or coaching. Most notably, several large-scale digital start-ups seized an opportunity in the midst of relaxed U.S. laws for prescribing stimulants (the main class of medications for ADHD) and began offering quick and easy online diagnoses to support their economy-of-scale business models. They unleashed a sea of digital ads upon their potential consumers (such as the post that caught Rebecca's eye). These ads also may have influenced self-referral rates for ADHD—through a digital start-up or otherwise. It is worth noting that a few ADHD-centric prescribing companies (such as Cerebral and Done) later fell under federal investigation for predatory practices and subsequently folded their controlled-substance–prescribing operations. At the very least, we can say that the internet had developed a vested interest in expanding the definition of who could benefit from ADHD-related products and services.

A growing women's movement within the ADHD community may also be increasing self-referrals for ADHD diagnoses. As the CDC and other sources reveal, the majority of adults seeking diagnosis and treatment for the first time are women in their 20s, 30s, and 40s. The 2020s have witnessed a powerful great awakening of women who came to identify with the ADHD diagnosis for the first time

by sharing lived experiences with one another online.

The surge among women makes sense. It is well established that ADHD has been diagnosed at lower rates in girls than in boys. Because research on ADHD has historically excluded girls, we do not fully know if this trend reflects a structural inequity, later onset of ADHD in girls and women (perhaps influenced by hormonal factors), or a lower prevalence of girls and women at the extreme end of the trait ADHD distribution (perhaps due to protective effects of being biologically female on the expression of ADHD genetic risks).

In a grassroots fashion, the ADHD women's movement is mobilizing around the sentiment that women with ADHD were missed en masse during childhood due to diagnostic criteria that favor men and boys. One action item of this ADHD advocacy space is a push to expand the *DSM-5* criteria to better address the clinical presentations of women with ADHD. The diagnostic implications of the ADHD women's movement are complex, and women are indisputably expanding definitions of what ADHD can look like. However, research has not yet sorted out best practices for identifying ADHD in girls and women.

ADHD's recent surge, however, is probably not just a societal change in how we define and recognize the disorder. Emerging research has revealed that, within an individual, ADHD can be highly unstable across the lifespan. Thus it's possible that more Americans are experiencing clinically meaningful difficulties with ADHD since the pandemic. Many, if not most, individuals with ADHD will meet formal diagnostic criteria for the disorder during some years but not others. Some research confirms that fluctuations in environmental demands can influence the ups and downs of an individual's ADHD. What's more, ADHD symptoms can wax and wane even in people without ADHD.

This way of thinking lines up with the idea that genes and environment work together in ADHD. In other words, whether someone's genetic risk for ADHD shows up in real life can depend on what's happening around them. So, if certain things in society made ADHD symptoms worse, people who were already on the edge of having ADHD might have started feeling a lot more symptoms all at once—and many may have looked for some kind of support at the same time, whether that meant medication, therapy, coaching, or even supplements.

This idea matches what psychologists Maria A. Rogers of Carleton University in Ottawa, Canada, and Jaidon MacLean of the University of Ottawa found in their 2023 meta-analysis: Around the world, ADHD symptoms went up during the pandemic. So, if ADHD symptoms got worse during the pandemic, and if people started talking about ADHD more openly on social media, it makes sense that in the early 2020s more people like Rebecca—who would traditionally fall into the gray, subclinical area—started wondering if they had ADHD. But what caused the jump in official diagnoses? One likely reason is the rise of easy-to-access telehealth services, such as those offered by online mental health companies. According to a 2024 CDC report, about one in five adults with ADHD got their diagnosis using online modalities, and half have used telehealth for ADHD care in the past few years.

Many individuals with ADHD will meet formal diagnostic criteria for the disorder during some years but not others. What's more, ADHD symptoms can wax and wane even in people without ADHD.

Difficult Diagnoses

What is a clinician to do? If an individual who normally has subclinical ADHD visits a clinic during a period when their symptoms spike into the clinical zone, should a practitioner provide a diagnosis of ADHD? Doing so is probably not overdiagnosis since the individual will likely meet all criteria for ADHD (*DSM-5* requires several symptoms to be present since childhood, not the full syndrome). In future years, the broader field will likely recognize ADHD's fluctuating course across the lifespan and the factors that trigger ADHD flare-ups. The ADHD diagnosis will inevitably become more inclusive as the science of ADHD's fluctuations translates into clinical practice.

Adults who recognize themselves in the expanding list of relatable, crowdsourced ADHD symptoms may be self-diagnosing or wondering about possible ADHD, and some may have raised this possibility with their health care providers. It is not clear whether adoption of the neurodiversity framework is as widespread among clinicians as it is on social media. However, there is certainly a growing tension between traditional and alternative ways of thinking about ADHD diagnosis within the clinician workforce. The supposition that clinicians must wade through a pit of what-ifs to unearth a largely unimpaired individual's true ADHD neurotype is a tall order for many. Although an individual's level of trait ADHD correlates highly with their genetic load for the disorder, there is no definitive biomarker for ADHD. Some people with elevated genetic risk of ADHD do not display the disorder. Other people with ADHD do not demonstrate a strong genetic load. Trait ADHD is influenced by an interplay of complex biological, psychological, and environmental factors.

To complicate matters, ADHD is best conceptualized as a bundle of cognitive subtraits (such as working memory, response to rewards, and the ability to inhibit one's behavior) that contribute to an overarching ADHD behavioral trait. People who achieve a high score on an overall trait ADHD behavioral checklist will show widely varying combinations of these cognitive subtraits. Thus, there are undoubtedly different neurobiological paths to ADHD, and the volume may be turned up or down on those paths based on a range of stable or transient factors. Since ADHD is

ADHD symptoms in *DSM-5*	other disorders with the same symptoms
difficulty sustaining attention in tasks	
often has difficulty organizing tasks and activities	
fails to give close attention to details or makes careless mistakes	mild neurocognitive disorder
distractibility	• major neurocognitive disorder • delirium • cyclothymic disorder • bipolar I disorder • bipolar II disorder • schizoaffective disorder
does not seem to listen when spoken to directly	
does not follow through on instructions	
fails to finish tasks	
forgetful in daily activities	
fidgets with or taps hands or feet	
squirms in seat	
leaves seat in situations when remaining seated is expected	
runs about or climbs in situations where it is inappropriate	
restlessness	• mild neurocognitive disorder • bipolar and related disorders—with anxious distress • depressive disorders—with anxious distress • generalized anxiety disorder • adjustment disorders • gambling disorder • tobacco withdrawal • cannabis intoxication • cannabis withdrawal
unable to engage in leisure activities quietly	
"on the go," acting as if "driven by a motor"	
blurts out an answer before a question has been completed	
difficulty waiting their turn	• major or mild frontotemporal neurocognitive disorder—behavioral variant • major or mild neurocognitive disorder—with behavioral disturbance
interrupts others	• major or mild frontotemporal neurocognitive disorder—behavioral variant • major or mild neurocognitive disorder—with behavioral disturbance
intrudes on others	• major or mild frontotemporal neurocognitive disorder—behavioral variant • major or mild neurocognitive disorder—with behavioral disturbance
reluctant to engage in tasks that require sustained mental effort	
talks excessively	

Adapted from M. K. Forbes, et al. 2023.

Adult ADHD can be difficult to diagnose because many of the symptoms overlap with other conditions. For example, restlessness is listed in the *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* (*DSM-5*) as a symptom of ADHD, but it also appears in people with bipolar disorder, generalized anxiety disorder, tobacco withdrawal, and a number of other conditions. Pinpointing the problem often involves lengthy neuropsychological testing.

such a neurocognitively diverse category, there is no objective cognitive test that can reliably confirm the diagnosis. Instead, we clinicians rely on documenting a stable, impairing pattern of observable behaviors consistent with ADHD that are substantiated by multiple individuals.

Right now, there are both vocal advocates and opponents of the neurodiversity framing of ADHD. I have also met open-minded clinicians who feel the neurodiversity framework makes a lot of sense but are hesitant to step away from upholding the strict impairment and childhood-onset criteria. They fear that the boundaries of ADHD will become far too subjective, which will bruise its credibility. They are very protective of a diagnosis that is clearly so disabling to those who meet its strict criteria.

ADHD has always experienced stigma from skeptics in the public and in the broader medical field. For various reasons, similar scrutiny has not been passed on to sister diagnoses such as autism spectrum disorder or learning disorder, or to spectrum-based medical diagnoses such as hypertension or diabetes. Since ADHD traits are on a continuum and can show up in the general population, the impairment and childhood-onset criteria have acted as important checks and balances. The diagnostic line will inevitably become much blurrier if we kick them out of place.

ADHD is already vulnerable to misdiagnosis, and so affixing an overdiagnosis narrative has been tempting to those outside the ADHD community. As a standard part of the adult ADHD diagnostic assessment, clinicians must wade through a complicated process of ruling out other disorders with overlapping symptoms. There are many non-ADHD-related factors that alter the neurochemical environment of brain structures implicated in ADHD. For example, psychiatric disorders such as anxiety and depression, side-effects of medications taken for reasons unrelated to ADHD, normal responses to stress or poor sleep, endocrine disorders, and transitions such as hypothyroidism or perimenopause can all cause ADHD-like symptoms. Differential diagnosis is often the most time-consuming part of a properly performed adult ADHD evaluation. Multiple, long encounters are sometimes needed to confidently complete

this process. Modern health care systems cannot always accommodate this level of due diligence, which creates a vulnerability to misdiagnosis.

Unify or Subdivide

But for just as many occasions where ADHD is improperly diagnosed, it also is likely missed. Many late-identified adults with ADHD initially come into contact with the mental health system for co-occurring diagnostic rates that cause public discomfort. Partitioning rather than discrediting ADHD may be a consideration. For example, over the past 75 years the *DSM* has partitioned the previously singular diagnosis of depression into separate categories that include major depressive disorder, persistent depressive disorder, disruptive mood dysregulation disorder, and premenstrual dysphoric disorder. Perhaps it is time to do the same with ADHD.

Many late-identified adults with ADHD initially come into contact with the mental health system for co-occurring diagnoses. Often, undiagnosed ADHD is at the root of these secondary complaints.

noses such as anxiety, substance use disorders, or depression. Often, undiagnosed ADHD is at the root of these secondary complaints, but it is missed by the untrained eye. Thus, for every adult ADHD overdiagnosis there is likely an underdiagnosis.

The COVID-19 pandemic created global exacerbations in mental health concerns and a subsequent influx of people seeking help for ADHD and other psychiatric disorders. This unprecedented demand for mental health support required an expansion of the provider workforce, which shifted new providers into the task of making first-time adult ADHD diagnoses. It appears that many primary care doctors and nurse practitioners stepped up to meet this need (as did instant-diagnosis digital start-ups, some of which have been accused of predatory practices). Newer providers may be more vulnerable than a veteran ADHD specialist to confusing ADHD for a mimic; they may also be more open to inclusive viewpoints on the nature of ADHD in adults.

Scientists have long understood ADHD as a collection of related disorders that impact self-regulation, making it vulnerable to becoming a catch-all category for anyone with attentional concerns. This diagnostic lumping may be expanding the inclusiveness of the ADHD category and producing diagnostic rates that cause public discomfort. Partitioning rather than discrediting ADHD may be a consideration. For example, over the past 75 years the *DSM* has partitioned the previously singular diagnosis of depression into separate categories that include major depressive disorder, persistent depressive disorder, disruptive mood dysregulation disorder, and premenstrual dysphoric disorder. Perhaps it is time to do the same with ADHD.

The process of subdividing ADHD into a broader class of multiple disorders must be done through careful research that examines the full implications of diagnostic changes. The vocabulary surrounding future changes is also important. As with depressive diagnoses, reorganization of a broader category of disorders of attention and self-regulation might consider severity (is there a lighter form of ADHD that mainly impacts psychological factors?), course (are there female sex–specific versions of ADHD with pubertal or perimenopausal onsets?), persistence and stability (is there ADHD that fluctuates with environmental factors?), and features (is there a form of ADHD that is largely experienced as emotional dysregulation?).

The critical point is that everyone's experience of ADHD-like difficulties, and their impacts on how one walks through life, are valid. Our diagnostic categories need to do a better job of capturing the many faces of ADHD and of helping patients and clinicians see eye to eye on diagnostic conclusions. Until diverse disorders of attention and self-regulation are properly sorted, ADHD will continue to become more and more inclusive as additional forms of self-regulation concerns are recognized and pushed into the only diagnostic category available to them. Despite the many reasons why diagnostic lumping is problematic, people like Jake and Rebecca still need help, and we want to make sure they can get it.

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Growing the Great Green Wall

A collaborative effort spanning the width of Africa is planting a verdant barrier of trees and traditional agriculture to protect the Sahel from desertification.

Maxim Samson

The heat is oppressive. Weary birds drift across the sky, yearning to escape the blistering Sun. Below, the soil is being baked to diamond hardness, its value diminishing with every moment. Grasses dry to matchsticks; skinny goats teeter and swoon. Hunger and despair are etched on the haggard faces of people who, with the shifting sands of time, reap little more than an early glimpse into an apocalyptic future, as a rapidly changing climate drives new population movements, new pressures, and new conflicts.

Stretching for approximately 6,000 kilometers from the Atlantic Ocean to the Red Sea, the Sahel is a continuous belt of semiarid land between the dry Sahara to the north and the wetter savannas to the south. Depending on one's definition, the Sahel intersects at least nine countries—Senegal, Mauritania, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, and Eritrea—and arguably the Gambia, Guinea, Guinea-Bissau, Cameroon, Ethiopia, and Djibouti as well.

Evidence of an extraordinary past remains in the architecture of various medieval cities along the region's main trans-Saharan trading routes. For the majority of the Sahel's inhabitants today, however, the fabled histories of Chinguetti in Mauritania (a popular gathering place for Muslim pilgrims heading to Mecca, and an important repository of Koranic texts) and Timbuktu in Mali (a flourishing and profoundly interconnected hub for scholars and traders that far outstrips its mythologized "far-off" reputation) are of little consequence. Marred by drought, poverty, disease, and bloodshed, this once-illustrious strip of land has metamorphosed into the world's biggest crisis zone.

As much as the Sahel refers geographically to the various lands joined together at the desert's edge, its contemporary connective relevance is far more fluid. The region ties together more than 100 million people who face challenges unimaginable almost anywhere else on the planet.

At the heart of the matter is *desertification*: The Sahara is now as much as 18 percent larger than it was a century ago. It is easy to blame this rapidly changing geography on climate change. Temperatures in the Sahel are rising 1.5 times faster than the global average and are projected to increase by another 3 to 5 degrees Celsius by 2050. Considering that in some places temperatures can already push 50 degrees, this region is quite literally feeling the heat more than anywhere else on Earth. Coupled with an abbreviated summer rainy season, especially in the west, and a winter dry season that is seeing increasingly intense winds from the Sahara bring thick clouds of dust, forests and fields are degenerating before people's eyes.

However, climate change is not the only impetus behind the growing desert. Alongside the Sahel's multi-decadal increase in temperature and decline in rainfall, human activities have left once-vegetated ground bare. Whether directly or not, an underlying cause is the Sahel's rapid population growth, as dazzling as the Sun overhead. By virtue of a well-founded fear that many children won't survive until adulthood, a widespread belief that more children means more chances of economic success, and religious and cultural expectations that champion large families over family planning, the Sahel is the most fertile region in the world—in terms of demographics. At a little less than seven children per woman, Niger's fertility rate is three times above the global average and over 70 percent higher than the average of the world's least developed countries. Add to that the fact that nearly two-thirds of people in the Sahel are under 25 years old, most of whom still have plenty of child-rearing years ahead of them, and it's clear that the region faces near-irresolvable dilemmas, both demographic and environmental.

Continued population growth here is a given: According to current projections, the region could be home to 330 million people by 2050, and double that by 2100. The problem is that productive land isn't expanding at the same rate. Worse, due to a combination of climate change and weak government regulations and oversight, it's diminishing. And so, with increasing pressure placed on fewer and fewer shreds of viable terrain to feed more and more people, deforestation, over-cultivation, and overgrazing now run rampant, driving the region's natural resources to a breaking point. When the rain finally falls—which it tends to do as torrential downpours—it can prove less a comfort than a curse, washing away the nutrient-rich topsoil, engulfing exhausted communities in floodwater, and attracting biblical swarms of desert locusts so dense they are capable of forcing passenger planes to divert.

QUICK TAKE

The Great Green Wall is an ambitious project to cultivate the Sahel region, which separates the dry Sahara Desert in North Africa from the wet savannas in Central Africa.

The initiative aims to bolster Sahelian communities by protecting them from desertification and providing stable sources of food, income, and security.

The success of the Great Green Wall hinges on local knowledge and expertise. Plans from well-intentioned outsiders have not accounted for the complexity of the environment.

Thierry Berrod, Mona Lisa Production/Science Source

The Great Green Wall is an ambitious initiative that began in 2007 to create an 8,000-kilometer barrier of verdant land across Africa that will protect the Sahel from desertification. Local communities from Senegal (*above*) to Djibouti contribute to the project by planting and tending to farms, gardens, grasslands, and forests. In turn, the rejuvenated land provides food, income, and stability to the residents of this historically fraught region.

Confronted with these taxing conditions, many Sahelians have opted to migrate to the few relatively arable provinces in the region, or to urban or coastal areas beyond. However, most of these migrants continue to face a series of modern plagues. Whereas for centuries herders tended to be welcomed by southern farmers because their animals would fertilize their fields, today violent clashes over increasingly scarce resources have become all too frequent, particularly where legal rights to land are inconsistent or unclear. Catalyzed by the rise of ethnically based militias, Islamist groups including Boko Haram and Islamic State have expanded across the Sahel, seeking to exploit these fragile states' general lack of political stability.

This medley of desertification, destruction, and disorder has undermined the prospect of meaningful gains being made in other key areas of society—the sort of advances that would help alleviate some of the problems at the region's root. Unrelenting violence has both exacerbated and been fueled by local communities' difficulties in accessing essential resources around the redundantly named Lake Chad (*Chad* literally translates as *lake*), a water body that shrank by more than 90 percent between the 1960s and 1990s, primarily due to climate change. In Burkina Faso, water and health care services have become entangled in combatants' military strategy: Each assault ensures that these necessities remain outside the reach of a growing number of people.

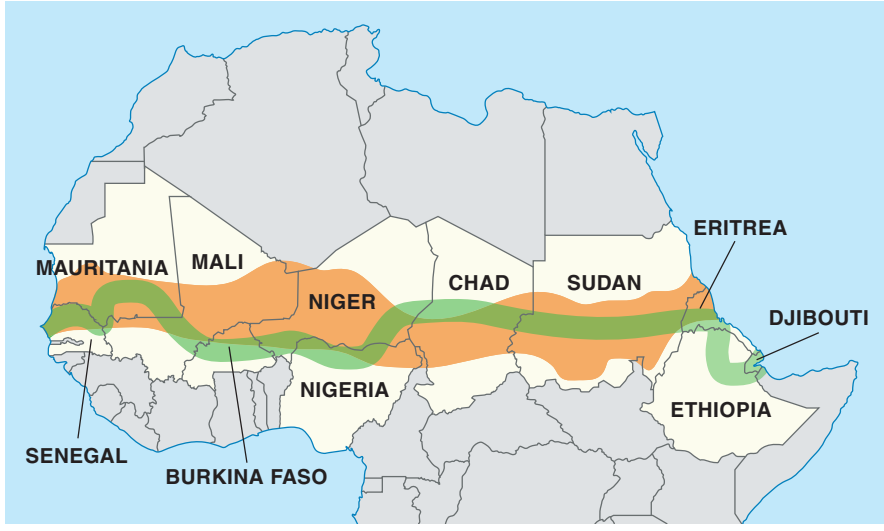
Yet beyond the region's trifecta of interconnected challenges—climate change, overpopulation, and conflict—a less widely recognized factor shapes and unites the Sahel. For centuries, nomadic and seminomadic groups have journeyed vast distances across the Sahel and Sahara, seeking to maximize the seasonal pastures in different regions without overexploiting them. Merchants and their camel caravans have traditionally relied on Indigenous groups' familiarity with the desert, following meticulously defined itineraries between oases to traverse some of the planet's most arid natural landscapes.

Although these relatively small numbers of periodic travelers have historically connected the Sahel in a somewhat tenuous way, today an ambitious initiative seeks to materialize the region's long-standing ties and bring overdue advantages to millions. In contrast to the many walls intended to divide and exclude, the Great Green Wall initiative—which was founded in 2007—shows that walls can have a productive, future-facing function. Both a barrier against desertification and a unifier of ruptured societies, the enterprise encapsulates the latent potential of geographical connection in restoring and reviving our world. The Great Green Wall demonstrates that, through mindful action, commitment, and collaboration, we can transform our broken surroundings.

Transition Zone

Meandering from west to east across sub-Saharan Africa, the Great Green Wall is an ongoing project to create the world's largest living structure, over three times longer than the world's current record holder, the Great Barrier Reef. At this endeavor's core is the earnest aim of restoring 100 million hectares of the planet's most degraded terrain by 2030, along an uninterrupted 8,000-kilometer course from Senegal to Djibouti.

Although the original plan was to connect Africa's west and east coasts with a continuous 15-kilometer-wide wall of drought-tolerant trees, the Great



MINUSMA/Marco Dormino/Flickr/CC BY-NC-SA 2.0; Sevgart/Wikimedia/CC BY SA 4.0

An aerial view of Mali (*top*) shows the landscape transition from the Sahara Desert to the Sahel, as shown in brown in this map (*bottom*). The Great Green Wall (*green*) aims to unite 11 countries (*white*) in an effort to revitalize both the land and the communities in the Sahel.

Green Wall has since evolved into a linear mosaic of productive landscapes, including forests as well as grasslands, savannas, farms, and community gardens. Even though the new vision may sound less grandiose, its construction is far more realistic. Practicalities are paramount: A wall broken up by long treeless gaps isn't really a wall.

In order for this project to succeed, each and every section needs to be intact. The Sahel, after all, is a necessarily interconnected region, where land degradation locally can quickly set in motion a domino effect of migration, resource pressure, violence, and extremism across a much wider area.

By contrast, regeneration promises to spark further benefits. The cultivation of food should act as a safeguard against malnutrition, still a life-threatening issue for millions of people in the Sahel. With enhanced food security, as well as the intended creation of 10 million green jobs in some of the world's most destitute rural areas, regional security will hopefully follow: Improved living conditions will provide less sustenance for the growth and spread of extremist groups, whose recruitment largely depends on exploiting citizens' vulnerability. And as if these remarkable advantages weren't enough on their own, the Great Green Wall's relevance stretches far beyond the Sahel. Through targeting the capture and storage of 250 million tons of carbon, the region—which contributes the least to global carbon emissions relative to its population size, yet is one of the most sensitive to climate change's impacts—would mitigate the planet's greatest existential threat. Given these varied and intrinsically international benefits, it is unsurprising that the Great Green Wall has captured the interest of a wide range of partners in the Sahel and beyond, including the United Nations, the World Bank, the African Development Bank, the European Union, the International Union for Conservation of Nature, foreign governments, nonprofits, and private actors.

With all eyes suddenly on the Sahel, the question then becomes: Who leads this revolutionary initiative? The answer, so obvious on the surface and yet sadly so radical in modern history, is Africans. For decades, sub-Saharan landscapes tended to be managed according to the priorities and assumptions of powerful people in distant places, uprooting Sahelian communities' distinctive management of familiar lands in the process. The Great Green Wall can be regarded as the culmination of this shift in emphasis, from the foisting of land-use practices to serve the needs of others, to timely interventions nevertheless conceived according to an outsider's assumption of Sahelian needs, to, finally, a project designed for Africans by Africans.

Sahelians Take the Lead

That said, as challenging as it is to transform lands, it can be just as difficult to change mindsets. The Great Green Wall epitomizes this unfortunate reality, because in its original, tangibly connective form, the project better resembled a distinctly foreign and flawed approach to restoring arid landscapes: mass tree planting.

What many rural Sahelian communities already knew, but the Great Green Wall's policymakers seemingly didn't, is that land degradation at the desert's edge is not owing to the desert itself; the Sahara only looks like it's advancing. The truth is, trees are not well suited to being anti-desert barriers—not unless the soil and water supply are improved first, anyway. Unfor-

G Gray Tappan/USGS

The landscape in the Ferlo region of Senegal changed significantly between 1994 (*left*) and 2011 (*right*). Photographs of the same site 17 years apart illustrates how desertification strips the land of vegetation, and that lack of ground cover provides fodder for sandstorms.

tunately, the initiative was forced to learn this lesson the hard way: Northern Nigeria noticed that three-quarters of its 50 million new trees had died within just two months. The original vision of connecting the Sahel with trees needed some significant tweaking, and quickly.

To succeed, local knowledge and expertise—which were largely overlooked in the first few years of the initiative—would have to constitute key building blocks. On top of the ecological challenges of growing trees on parched lands, it was implausible to expect time-poor communities to travel long distances to the remotest areas of the Sahel to tend to saplings, or to refrain from clearing trees whenever they needed fuel. Cognizant of these issues, in place of a one-size-fits-all strategy of creating a coast-to-coast line of trees, the Great Green Wall has come to represent a varied patchwork of sustainable land and water management practices, in which communities restore their lands in ways that best retain and respect their uniqueness, while serving their own fundamental needs. It may be less obviously connective than its foreign-inspired roots, but in both its heterogeneity and its groundedness, the new Great Green Wall is genuinely African.

Is it still a wall, though? Reflecting the symbolic power of lengthy, connective landmarks, the concept of a green wall is so irresistible that the name has remained in place even as the program has evolved from a straightforward tree barrier into a far more comprehensive rural development initiative. In emphasizing a collaborative approach to creating lush, productive landscapes that are distinct from one another and yet interconnected, this strategy represents a reworking rather than a renunciation of the initial vision. It doesn't matter that it won't look like a wall per se. As long as it is able to achieve the objectives of the original vision, devoid of holes where land practices continue to exacerbate desertification, it will serve as a wall-in-kind. Ultimately, the benefits are all that really matter; the rest is just semantics.

Each "brick" of the Great Green Wall has its own idiosyncrasies appropriate to local conditions and knowledge.

Each "brick" of the wall has its own idiosyncrasies appropriate to local conditions and knowledge. In northern Burkina Faso and neighboring areas, for example, a traditional agricultural technique for increasing soil fertility called *zaï* (elsewhere known as *tassa* or *towalen*) has been revived, enhanced, and rolled out ever more widely since the early 1980s, thanks in no small part to the vision and energy of the late Burkinabé agronomist Yacouba Sawadogo. This method, which involves digging a grid of small pits into degraded soil and placing a couple of handfuls of organic matter at the bottom to attract termites, offers important advantages in regions where the soil is infertile, rainfall is sporadic, and resources are scarce. The termites dig tunnels in the ground, allowing more rainwater to infiltrate into the soil, and process the organic matter so that nutrients in the soil become more readily available to any seeds carried into these moist pockets by wind, rain, or hand. With the endorsement of farmers cultivating significant yields of millet and sorghum, zaï has become an increasingly common feature of long stretches of the Great Green Wall's western segments, bringing new, verdant life to landscapes that only recently seemed beyond repair.

Other agricultural practices similarly manifest a frugal use of local materials, and despite their varied appearance, they share the objective of capturing as much of nature's essential resources as possible. Often conjointly with zaï, and particularly where there is a slight gradient, many western Sahelian farmers choose to place rocks along natural contours to create long stony bunds or lines. When the rain falls, these unbroken barriers slow surface runoff so that more water soaks into—rather than rushing away from—farmers' fields, while trapping valuable sediments and organic matter.

In Niger, another popular method on gentle slopes is to construct cres-

Michael Dwyer/Alamy Images

Indigenous land cultivation practices, such as this *zaï* garden in Mali, have had greater success regreening the region than imported agricultural and land management systems. Using the zaï method, farmers deposit organic material into a grid of small plots. The material attracts termites, which then do the hard work of aerating and enriching the soil.

cent-shaped bunds called *demi-lunes* (half-moons) capable of trapping surface runoff and organic matter immediately following rainfall. In the clay plains of eastern Sudan, series of interconnected U-shaped earthen bunds, called *teras*, are traditionally used to prepare the soil for the cultivation of Indigenous cereals such as sorghum (which can tolerate both drought and temporary waterlogging), while in Eritrea and Ethiopia terrace farming is being expanded along the slopes.

In Chad, the prehistoric practice of forest gardening has been modernized as a regenerative agroforestry technique, whereby carefully selected trees are intentionally integrated with fruit and vegetable crops to create a biodiverse and self-perpetuating ecosystem. With the significant support of the U.S. nonprofit organization Trees for the Future, this strategy is, in effect, creating a green wall both edible and defensive, providing local communities with food and medicine, and protecting crops from wind and water erosion.

Most eye-catching of all are Senegal's *tolou keur*, community gardens comprising a series of concentric circles. The outer halo of these gardens is made up of drought-resistant trees such as baobab and mahogany, which protect the smaller rings of food-producing and medicinal species within. Conceived by the Senegalese agricultural engineer Aly Ndiaye as a necessary response to declining imports, among other disruptions, during the COVID-19 pandemic, tolou keur are now regarded by local communities as essential laboratories for further experimentation as well as resource provision. Along with curving permeable rock dams, round *bouli* ponds, strip-like rainwater trenches, V- and diamond-shaped micro-catchments, webs of live fences and field hedges, and parallel plowed troughs, these human interventions are helping to shape distinctly geometric landscapes across the Sahel.

Thanks to the opportunities provided by the initiative for knowledge sharing across vast distances, various modern methods, including some conceived by people foreign to the Sahel, are also now being implemented throughout the region. Perhaps none is more noteworthy than *farmer-managed natural regeneration* (FMNR), which, having been successfully pioneered by the Australian agronomist, missionary, and "forest maker" Tony Rinaudo in Niger in the early 1980s, is today being replicated across swathes of the western Sahel. FMNR's rather inelegant name conceals its conceptual simplicity. Effectively, it requires farmers to take a relatively hands-off approach to their fields, intentionally not planting any trees and instead systematically pruning and nurturing those species that sprout spontaneously from the soil. FMNR thus offers an ideal balance between the human and natural worlds, neither allowing the land to go fully wild, nor clearing or farming it to excess, all while enabling farmers to benefit from trees' ability to protect their crops from wind and windblown sand and to supply fodder for their livestock.

What this assortment of strategies brings to light is a growing appreciation that cutting-edge, high-tech, but generally inflexible solutions requiring expensive maintenance are not the Sahel's reality. Simple, low-cost improvements on locally familiar practices tend to be far more appropriate to the region's resource-scarce environment, with the very best options being those capable of addressing multiple needs simultaneously. Just as climate change, desertification, and biodiversity loss operate as a vicious cycle trimming residents' incomes, land rehabilitation can increase groundwater recharge and also support the development of farms and vegetable gardens capable of feeding stomachs and wallets.

If its reported statistics are to be believed, so far nowhere has been more adroit at rehabilitating its lands than Ethiopia. At the beginning of the 20th century, forests covered 40 percent of Ethiopia (and 90 percent of its highlands), but rampant deforestation, especially in the first half of the country's communist Derg dictatorship in the mid-1970s and early 1980s, left only 4 percent of its lands forested by the turn of the millennium. However, Ethiopia also has a long tradition of seeking symbiosis between the human, natural, and spiritual worlds, represented best by its tens of thousands of *church forests*. Miniature Gardens of Eden, these ring-shaped woodlands, some of which are now safeguarded by stone walls, continue to be preserved as extensions of the sacred sites they surround, and in return offer congregants space for contemplation and protection from wind and heat.

Ethiopia's church forests can appear like extraordinary remnants of a lush past, and yet the country's viridescent history may not be as lost as it once seemed. Aided, no doubt, by the country's recent issuance of landholding certificates to more than 360,000 households, public buy-in regarding its ongoing Green Legacy initiative is quite astonishing. By 2020, Ethiopia claimed to have restored 12 million hectares

of degraded land (mostly outside the official Great Green Wall intervention zone), representing over two-thirds of the initiative's total to date, and putting the country 80 percent of the way toward its own 2030 target. Reflecting its inhabitants' deep-rooted reverence for trees, Ethiopia subsequently reported the planting of 25 billion seedlings between 2019 and 2022, and is currently striving to emulate this achievement by 2026. Most remarkably of all, on July 17, 2023, millions of Ethiopians from all walks of life collaborated to plant more than 500 million trees, beating the country's previous record of 350 million, set four years earlier. Even though it's possible that the Ethiopian government has been a little cavalier with its data, any achievements even remotely close to these figures deserve to be congratulated rather than scorned.

Another major success story is a nation at the opposite end of the Great Green Wall, Senegal, where the planting of 12 million native trees in less than a decade seeks to protect crops from fierce gusts and citizens from economic insecurity. Within its rejuvenated tree belt, perhaps no species better encapsulates this country's shrewdness than a thorny tree whose scientific name, *Senegalia senegal*, affirms its indigeneity and hence its natural survival advantages there. This acacia also provides huge economic value: Its gum arabic is used as an emulsifier in soft drinks and confectionery, as a base material in incense, as a thickener in shoe polish, and as a binder for watercolor paints. The species is therefore almost as immune to deforestation as it is to drought.

Having long been dismissed as the world's most hopeless region, the Sahel is emerging like a phoenix, resurrected from disaster through the foresight, know-how, and verve of African people. The Great Green Wall in its modern iteration epitomizes a growing recognition internationally that Sahelian people can take charge of their own affairs. The region's farmers are increasingly lauded for sharing their innovative cultivation methods with their counterparts throughout the region. In so doing, they are, in effect, transcending the borders created by colonial powers in the past. In this sense, the Great Green Wall's significance is not merely environmental: It also represents a mutual, physical intermediary between people whose historic affiliations have been largely erased from the map. With a clear and shared vision for the region's future now in place, certain stretches of the Sahel are gradually being transformed into flourishing emerald landscapes, with a view to one day becoming interlocking stakes of this expanding palisade.

Reuters/Zohra Bensemra

***Tolou keur* gardens in Senegal consist of concentric circles of plants protected by a shield of hardier, drought-resistant trees (*shown here in the early stages of planting*). The design was developed during the COVID-19 pandemic when imported foods and materials were scarce.**

Unifying Effort

Few initiatives can claim to be as inspirational as the Great Green Wall in attempting to unify broad and diverse societies with a shared, pressing purpose. In the region most severely affected by land degradation and desertification, where the soil is thin and rain is unreliable, here is a project whose mission is to grow not just plants, but also the fertile ground on which they rely. In countries where extreme poverty is a fact of life for millions, the Great Green Wall is an opportunity to create new economic opportunities, harnessing nature's resilience to glean value from its most essential resources. Long marked by desperation and division, the Sahel may seem an unlikely place to find connection. But should the Great Green Wall mature and ripen as a fully integrated architecture of green and productive landscapes, as the uninterrupted green river from ocean to sea depicted on the initiative's official emblem, it will be living proof that humanity can work together to change itself and its environments for the better. More than just a symbol of African ingenuity, with the potential to alter how the continent is perceived internationally, and more than just a show of political will at the global scale, the Great Green Wall will

The Great Green Wall's significance is not merely environmental: It also represents a mutual, physical intermediary between people whose historic affiliations have been largely erased from the map.

Si Yuan/Xinhua/Alamy Live News

Solar panels in the China-Africa Green Technology Park in Mauritania are part of the African Development Bank's effort to turn the Sahel into the world's largest solar zone. The clean electricity generated would power irrigation systems in the Great Green Wall and would provide clean energy to the area's inhabitants, which would mean lower emissions and fewer trees cut down for fuel.

be a proclamation to the rest of the world that the future never need be inevitable. If the world's most disadvantaged region can overcome its greatest threats, then surely anywhere can.

As testament to its international relevance, the Great Green Wall makes important contributions to a staggering 15 of the UN's 17 Sustainable Development Goals (SDGs) for a better world by 2030 and all three of the conventions (on climate change, biological diversity, and desertification) created by the renowned 1992 Earth Summit in Rio de Janeiro. It also supports the UN Convention to Combat Desertification (UNCCD) and SDG 15's shared objective of achieving land degradation neutrality by 2030. It also acts as a flagship for the present UN Decade on Ecosystem Restoration and complements the African Forest Landscape Restoration initiative's pledge to the Bonn Challenge, which seeks to restore 350 million hectares of degraded and deforested land by 2030.

Already, the project has served as a green light for other endeavors whose mission is to advantage people and places with the biggest need. Impressed by the progress being made in parts of the Sahel, and conscious of the failures of its past decision to plant Aleppo pines (which demand lots of water, are susceptible to disease, and have limited use for local communities) as the basis of its own green barrier, Algeria has opted to relaunch its afforestation project with far greater species diversity than before. At the other end of the continent, plans to create a southern Great Green Wall are quickly taking shape, again with an emphasis on uncovering, rejuvenating, and sharing Indigenous farming techniques suited to drylands, including the Kalahari and Namib deserts and South Africa's Karoo.

When it comes to restoring degraded lands, collaboration among stakeholders, countries, and projects is essential: One must not lose sight of the fact that improvements to water, soil, and vegetation are mutually reinforcing, and act as the key to solving a broad range of economic, social, and political issues. Accordingly, a multitude of initiatives in the Sahel have been directly harmonized with the Great Green Wall, from renewable energy to food security, and from climate resilience to species conservation.

For instance, the African Development Bank's ambition to create the world's largest solar zone in the Sahel, capable of supplying clean, renewable energy to a quarter of a billion people across the 11 original Great Green Wall countries by 2030, is explicitly tied to the initiative. For one thing, by drastically reducing energy poverty throughout the Sahel, this Desert to Power Initiative ought to dissuade residents from cutting down the trees grown throughout the region for fuel. For another, through introducing solar-powered drip-irrigation systems, which enable farmers to grow more crops with less water and energy, the project aims to increase agricultural productivity and food security—both key elements of the Great Green Wall's mission as well—while deterring people from practicing less sustainable methods that threaten the wall's integrity.

Rather than being simply a barricade against the desert, the Great Green Wall has also become a bridge, bringing together various people and places in the intricate and knotty fight against land degradation, ecosystem damage, climate change, and extreme poverty and hunger. Backed by phenomenal political will on an international scale, the initiative's consequentiality—real and symbolic, local and global—is hard to overstate.

Challenges and Progress

As a rare but necessary example of the contemporary Sahelian nations working together, the Great Green Wall uses the power of connection to mitigate and reverse this vast belt's most formidable perils. The problem is that the same qualities that provide cause for hope and which might hold the endeavor (and, by extension, the region) together also risk tearing it apart. The initiative, in short, is characterized by paradoxes that threaten its eventual realization.

First is the fundamental but thorny matter of whether the Great Green Wall is a top-down initiative overseen by a central body (in line with the original tree-barrier vision), or a genuinely bottom-up enterprise led by different local communities (as implied by the new concept). In reality, the project now resembles something of a mishmash, being nominally coordinated by the Pan-African Agency of the Great Green Wall (PAAGGW), a Mauritanian-based regional authority that finds itself regularly bypassed by funders keen to control how their contributions are spent. PAAGGW and the African Union have struggled to determine how much money is available, who is funding what, and whether the finances represent loans, grants, or otherwise, the conditions for which vary greatly.

To complicate matters further, the Sahelian countries are often hesitant to accept loans, particularly for environmental projects, fearing that they will only compound their ceaseless and traumatic debt crises. Together with a relative lack of independent research tracking how much funding each country has mobilized and the progress it has made toward its targets (how many planted trees have actually survived, for instance), the question of

who does or should lead the initiative risks frustrating its future.

An associated paradox pertains to donors. Although the initiative is directly relevant to a wide range of environmental and development objectives, due to its sheer scale and scope—not to mention a paucity of centralized information about specific Great Green Wall programs—prospective donors often struggle to determine where and how they should help. And even though the Great Green Wall's emphasis on community participation ought to encourage local populations to contribute, because it comprises numerous smaller projects necessarily distinctive to local contexts, there is a real risk that many will be treated as discrete silos or will remain out of the limelight necessary for attracting wider investment.

So far, Ethiopia and Nigeria have been among the most proactive partner countries in obtaining funds and implementing new projects, but owing to the considerable strain applied by their rapidly growing populations across significant portions of territory, they are also under the most pressure to continue attracting financial support, certainly compared with far smaller nations such as Djibouti. Size commands the attention of funders, but it demands that they spend more as well.

A further challenge with managing such a colossal project simultaneously from the grassroots and from above is ensuring close alignment between parties. Despite the theoretical flexibility of the Great Green Wall as an umbrella initiative, national land-use laws, particularly with regard to tree felling, still tend to demand burdensome and slow bureaucratic procedures, which can sap enthusiasm for the initiative.

In much of the western Sahel, the mixed legacy of customary law and colonialism means that agricultural and pastoral lands continue to be owned by the state. Additionally, rural residents can find it far harder to obtain legal title to lands their families have managed for generations than do foreign investors and loggers, whose interests tend to be narrower and whose actions are more likely to be exploitative. As a consequence, many communities are understandably reluctant to engage in sustainable practices such as FMNR or even to grow trees in the first place: Not only do they see little incentive to manage trees, but doing so also risks punishment from powerful figures already liable to treat them with suspicion.

It doesn't matter that Indigenous peoples globally are incomparable stewards of the environment, protecting as much as 85 percent of the planet's biodiversity despite representing less than 5 percent of its population. In the Sahel, the established logic is that the authorities know best. Yet without local knowledge, engagement, and collaboration from West to East Africa, there will never be a Great Green Wall.

The question of whether the Great Green Wall is a truly unified initiative or a miscellany of small-scale schemes looms large again: Oversight from above is crucial to integrating diverse projects into a continuous strip of regreened land, but if local residents are unable to take ownership of their own needs and undertake practices that make sense to them, there will be little to connect.

As long as the wall has cracks, it is effectively just a loosely affiliated collection of gardens, beneficial to local residents in select areas but unlikely to bring lasting peace further afield.

As long as the wall has cracks, it's effectively just a loosely affiliated collection of scattered gardens, beneficial to local residents in select areas but unlikely to bring lasting peace further afield. And at the time of writing, the existence of mere cracks would be regarded as a triumph. Africa as a whole saw a far larger net loss of forest area than any other part of the world between 2010 and 2020; and as of 2023, the Great Green Wall remained just one-fifth of the way toward its land restoration target.

Recognizing these obstacles is not to understate the Great Green Wall's laudable achievements. Over time, the landscape of much of the Sahel is becoming increasingly heterogeneous and complex, its fields boasting a growing diversity of flora while its pastures accommodate larger herds of cattle, goats, and sheep. Even though plenty of young adults still believe, not without valid reason, that their job prospects are superior in sub-Saharan Africa's swelling cities, a good many others are increasingly willing to stay and work together to bring life to injured plots. A new "ecopreneur" class has emerged among women, who, instead of spending significant portions of the day collecting wood for fuel, can tend to community gardens and manage shops. More and more children enjoy diverse, nutritious diets, setting them up for success at school. These accomplishments all provide real hope that the world's most disadvantaged region is sprouting a better future for its inhabitants. The challenge is to close the wall's many remaining gaps.

Walls are often viewed as forbidding entities conveying separation and hostility. The Great Green Wall has no such patina. It proves that walls don't need to need to isolate deprecated communities. Instead, they can provide insulation against real issues, both human-made and natural, which in one way or another affect us all (and for which, through our consumption habits and energy use, we are in turn at least partly responsible). If completed as planned, the Great Green Wall will, in essence, be both a symbol of hope as well as a vehicle of peace and prosperity, protective and productive all at once.

Maxim Samson is a geographer and an adjunct professor at DePaul University in Chicago. *Reprinted with permission from* Earth Shapers: How We Mapped and Mastered the World, from the Panama Canal to the Baltic Way *by Maxim Samson, published by the University of Chicago Press. First published in Great Britain in 2025 by Profile Books Ltd.* *Website: www.maximsamson.com*

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The Solace of Darkness

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Ken Cheung/Pexels

What Goes In Must Come Out

Lisa Sanders

EARTHLY MATERIALS: Journeys Through Our Bodies' Emissions, Excretions, and Disintegrations. Cutter Wood. 384 pp. Mariner Books, 2025. $29.95.

As soon as I read the title of this book, *Earthly Materials: Journeys Through Our Bodies' Emissions, Excretions, and Disintegrations*, I knew I had to review it. For most people, those words—"emissions," "excretions," and "disintegrations"—are humiliations of the body that, with any luck, are never discussed with anyone else—ever. Yet here they are, fully exposed.

Author Cutter Wood is not a scientist. He's not a physician, duty bound to sometimes ask about these bodily products. He's a guy with an MFA and an interest in these gross bodily outputs—mucus, stool, blood, breath, and flatus. Simply based on that, I was ready to follow him deep into the nooks and crannies of our various corporeal factories and their emanations.

And Wood is ready to *go there*, right from the start. The book opens with a fart joke. Sure, it's found stamped in cuneiform from an anonymous Sumerian some two thousand years before the birth of Jesus, but it's still a fart joke. Wood goes on to show how our effluvia shaped our culture, our architecture, and our societies. That contrast characterizes much of this delightful and weird book. Beneath each chapter heading, Cutter includes a pithy quotation from a thinker drawn from history, ranging from the 4th century theologian Augustine of Hippo to the contemporary poet Claudia Rankine. Such dignity is balanced by a list of the other words the specific substance goes by, ranging from delicate euphemism to the shouted expletives of the joyful eight-year-old discovering the thrilling grossness of the body. For instance, the chapter on vomit starts with a line from the Bible then drops down to the schoolyard, as shown below:

> As a dog returns to his vomit, so a fool returns to his folly.
> Proverbs 26:11
>
> Terms
>
> n. barf, puke, throw-up, spit-up, mess, chunks, lunch, cookies
>
> v. barf, yarf, spew, spit up, burp up (mostly in infants) . . . chunder, yak, ralph, regurg, blow chunks, boot, bow down before the porcelain goddess, drive the porcelain bus, Technicolor yawn, bushusuru (Japanese, translating literally as "do a Bush" after former president George H. W. Bush inadvertently vomited on then-prime minister Kiichi Miyazawa) . . .

Images depicting some aspect of the specific excretion come next, ranging in tone from an elegant photograph of a crystallized tear to a 19th-century drawing by the Japanese artist He-Gassen, of what is described as a "fart battle."

After each chapter's introductory definitions and images, Wood provides a soupçon of science, which the author calls a "biological prologue." He then takes the reader through history, culture, philosophy, and personal anecdotes to focus on one aspect of each emission. For example, readers learn about a lab at the Massachusetts Institute of Technology that studies mucus, go deep into Reddit to assess sentiments about masturbation, and read about a business in Florida run by a suburban mom who is now serving time for trafficking in stolen baby formula.

Chapters are named after bodily fluids and most chapters are structured

around two or three anecdotes linked to that substance. "Blood" opens with a story about a friend who discovers that she has BII (blood–injection–injury phobia), which triggers a significant physical response that results in fainting, while walking past a local church holding a blood drive. After Wood explains that even saying the word "blood" can be extremely triggering in some people with BII phobia, he provides a historical review of its etymology before taking a deep dive into the big business of blood that is not often seen by those who are donating said product. As he lies on a stretcher donating a pint of his own, the author muses about the motivation leading him and the dozen other co-contributors to give away their literal lifeblood.

Our largesse with our blood, Wood notes, is often triggered by tragedy. It can therefore be a little demoralizing to find out what then happens to the blood so freely given away: It's sold. It's a product that goes to pharmaceutical companies, academic research centers, and of course, hospitals. He writes,

> And suddenly what you gave away for free ends up costing that kid with cancer a few thousand dollars . . . and the miraculous red stuff you thought was a big altruistic middle finger in capitalism's face turns out to have been just another commodity on another market in a world where everything gets bought and sold eventually.

Wood's storytelling style and approach to his material vary. In one chapter, he delves deep into a subreddit dedicated to the topic of not masturbating. In another, he dips in and out of his own boyhood traditions surrounding flatulence, and hides historic digressions within a series of David Foster Wallace–length footnotes. Combined with the author's casual (and sometimes gleefully gross) tone, the book can feel more like a series of blog posts than a collection of formal essays.

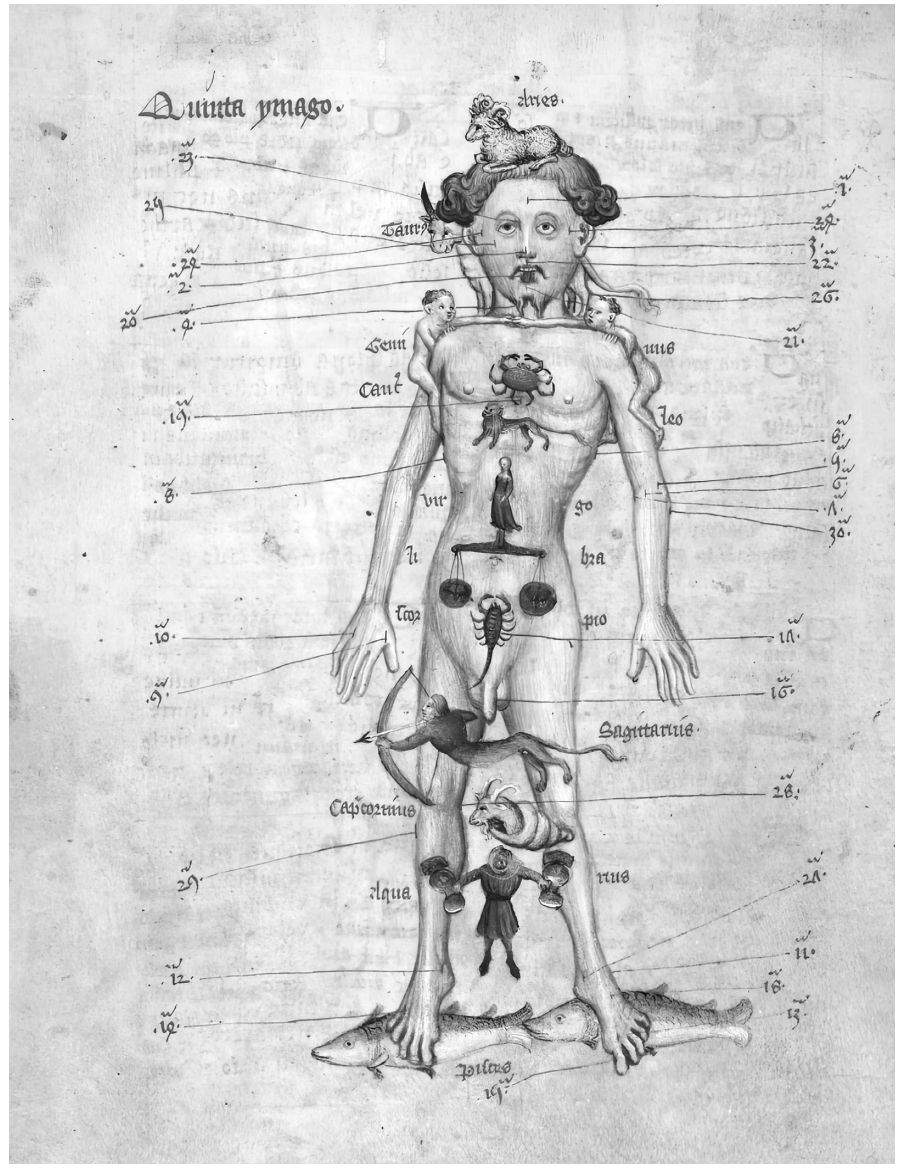
Wood also has an unfortunate love of lists and a grad-school-nerd glee in references that (at least for me) necessitated frequent Google searches that interrupt some of these otherwise entertaining pieces. But I forgave him when I found that the best place to read these brief treatises was in the bathroom, where I would have taken my phone anyway. Given the experience of reading the news these days, leafing through *Earthly Materials* is a much better way to spend these few moments of privacy.

The book ends with a summation of the earthly matters each of us leaves behind. It's a humbling inventory:

14,000 liters of feces
33,000 liters of urine
6,000 liters of tears
2 to 3 liters of menstrual blood
100,000 liters of mucus
2 million feet of hair

Then, at the end of life, there is the body itself, with all its proteins and fats and bones. But what we really leave behind that lasts, concludes Wood, are words. And if you are a certain kind of person, you will perhaps collect those words in a book—an object that, with luck, will live on. Fingers crossed, Cutter Wood.

With every topic, and with every emission that Wood takes on, he reminds us that "there's more to discover, as every child recognizes when



Medieval bloodletting diagram, *Liber Cosmographiae*, John De Foxton, 1408

Bloodletting, a practice made popular by Hippocrates and Galen, was said to bring the body into balance. Reducing the volume of blood in the body would cause a kind of homeostasis and cure diseases such as fever, cholera, or seizures. Where the incision was made depended on the ailment that needed curing, along with the position of the zodiac. The practice of bloodletting was adopted by various people throughout history, including notable figures such as George Washington, John Adams, and Thomas Jefferson.

they put their finger up their nose. It's all a matter of how far you're willing to go." And on these matters, Wood is willing to go all the way.

Lisa Sanders is an internist and professor of medicine at Yale Medical School. She is currently the medical director of Yale's Multidisciplinary Long Covid Care Center. Sanders also writes the popular and long-running Diagnosis *column for* The New York Times Magazine*, and is the author of the bestselling book* Every Patient Tells a Story: Medical Mysteries and the Art of Diagnosis.

Preparing for Apollo

Amy E. Foster

GEMINI: Stepping Stone to the Moon, the Untold Story. Jeffrey Kluger. 304 pp. St. Martin's Press, 2025. $32.

In his new book, *Gemini: Stepping Stone to the Moon*, Jeffrey Kluger—perhaps best known as the coauthor of *Apollo 13*, the book that served as the basis for the movie by the same name—provides a thorough history of NASA's Gemini program. Gemini bridged the Mercury and Apollo programs, launching a total of 12 missions between April 1964 and November 1966; 10 of these missions carried a two-astronaut crew. NASA used Gemini missions to test the skills and equipment needed for a successful moon landing and, while often overlooked, the program was essential to America's eventual mission to the moon.

Kluger argues that Gemini had

> . . . an outsized and often unappreciated impact on geopolitics, technology, and the fundamental science of space travel itself. It was the Gemini, certainly, that gave the U.S. the cosmic edge over the Soviet Union in the original space race, contributing to the cascading series of economic, engineering, and political victories that helped bring the original Cold War to a peaceful end, with the West ascendant and the former Soviet Union consigned to history.

The rest of the book catalogues the accomplishments of the Gemini program, in contrast to the lack of progress by the Soviets in the space race, and the effects this had on American society.

In May 1961, John F. Kennedy voiced a commitment by the United States to put a man on the moon and return him safely to Earth. That endeavor became known as the Apollo program. But when Kennedy made that speech, only one American had been into space (Alan Shepard) as part of the Mercury program, which ran from 1958 to May 1963. By the end of Mercury, six Americans had been into space and four had orbited the Earth, with the longest flight lasting a little more than 34 hours. But it was going to take three days to get to the moon, not to mention the trip home. In addition, Apollo required a much bigger, much more powerful rocket, the Saturn V. To meet Kennedy's goal by the end of the decade, NASA needed to develop a number of new technologies and to practice important skills. Waiting until the Saturn V was ready to fly to test all those new elements practically guaranteed missing that deadline. Kluger explains that the Gemini program, using the U.S. Air Force's Titan rocket, was the proving ground for those skills and technologies. Those skills—rendezvous and docking, spacewalking, and long-duration flight—together remain the basis of human spaceflight today, as astronauts have constructed and occupied the International Space Station as we plan for returning to the moon and then going to Mars.

NASA/Wikimedia Commons

Enhanced photographs of the Gemini missions were recently made available online to the public by NASA. This photograph captures astronaut Ed White, performing the first-ever EVA (extravehicular activity) for NASA, on June 3, 1965, as part of the Gemini IV mission. He was the first American to do an EVA, and enjoyed the experience so much that he didn't want to end the exercise and had to be ordered back into the spacecraft.

Kluger's retelling of the Gemini program's history is not entirely new, especially to space historians. However, he pairs official histories of the Gemini missions along with interviews he conducted to highlight just how important this program was to the overall success of the space race. During much of Mercury, the United States' space efforts lagged behind the Soviet Union's. Kluger's narrative emphasizes just how many challenges remained at the end of Mercury that the Gemini astronauts, NASA engineers, and contractors had to overcome. Kluger goes so far as to claim that "without Gemini, men would never have walked on the moon."

Throughout the text, Kluger elaborates on the challenges that the Gemini program faced before its first flight. He brings in the voices of engineers working on the program, highlighting its complexity and all that it needed to achieve. For example, he details some of the issues with the development of the Titan rocket, particularly a phenomenon known as *pogo*. This occurs when the pressure in the fuel tanks or fuel lines fluctuates to the point that the vehicle bounces around like a pogo stick. Pogo added significant g-forces that the astronauts would have experienced, to the point that they could have been injured or incapacitated. There were also concerns about the escape system, should there be an emergency during or just after launch. Kluger illustrates how the engineers worked to solve such problems, and the pressure felt by everyone in the Gemini program. He writes, "If Gemini was indeed about to fall on its face, it meant NASA would, too, and if NASA failed, it meant that in the eyes of the world, America would be losing the space race."

The second half of the book provides detailed accounts of the 10 crewed Gemini missions that took place between March 1965 and November 1966, with just over two months between each launch. These stories are well-documented in NASA flight journals that are available to the general public, but Kluger brings them together in a more accessible narrative that emphasizes how significant this program was to the ultimate success of Apollo.

What NASA accomplished over the course of the Gemini program in many ways showed that the United States was pulling ahead in the space race, which Kluger documents by providing a side-by-side comparison to the Soviet activity during the same period. He notes that for the entire 603 days that Gemini had been flying, the Soviets did not launch a single person into space. More importantly, NASA used the Gemini program to develop all the essential skills for going to the Moon while engineers built and tested the new Saturn V rocket, the Command Module, and the Lunar Module that would make a Moon landing possible.

But the long list of challenges that NASA faced in putting a man on the moon were solved because of Gemini.

While other books highlight the technical aspects of the program, *Gemini* emphasizes the idea that the Gemini program was a key turning point in the space race, not just a stopgap program to keep America flying before Apollo was ready. The importance of this program to the success of Apollo and the end of the space race gets overlooked by the general public because it was not sexy, patriotic, or triumphant in the ways that Mercury and Apollo were. But the long list of challenges that NASA faced in putting a man on the moon were solved because of Gemini. The glory belongs to those lesser-known engineers and astronauts who made the program possible, and Jeffrey Kluger deserves credit for bringing this program's significance to the general public's attention.

Amy E. Foster is an associate professor of history at the University of Central Florida. Her research and teaching cover the history of the United States space program, as well as the history of science, technology, and medicine.

Body Parts, Reimagined

Jason M. Organ

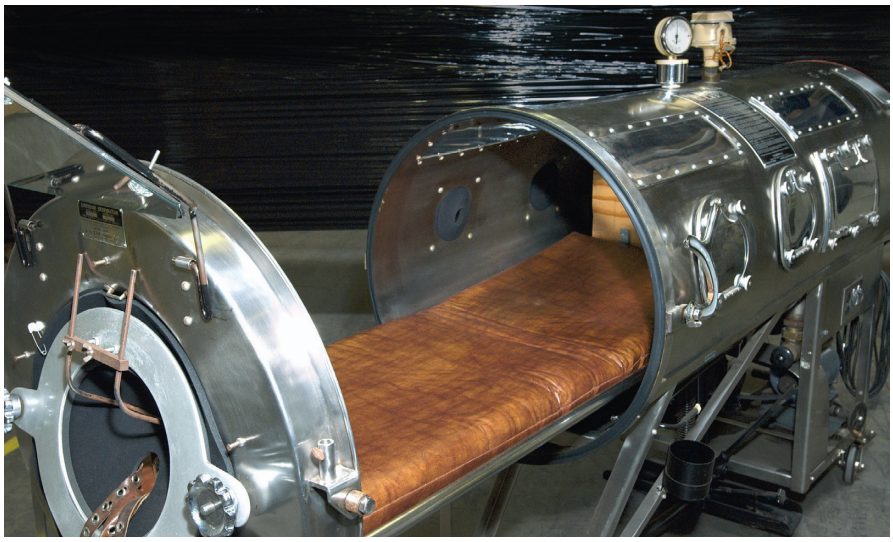
REPLACEABLE YOU: Adventures in Human Anatomy. Mary Roach. 288 pp. W. W. Norton & Co., 2025. $28.99.

If you've ever wondered whether a sheep could donate skin to a human, or whether a colon could moonlight as a vagina, Mary Roach has answers for you. From cadavers (*Stiff*) to digestion (*Gulp*), sex (*Bonk*), and the afterlife (*Spook*), her books have made complex biology accessible and engaging for a wide audience. In her latest, *Replaceable You: Adventures in Human Anatomy*, Roach slices into the world of anatomical substitution with her signature scalpel-sharp wit and a bedside manner that's equal parts curious and compassionate.

Replaceable You isn't just a book about body parts, though: It's also a book about the people who lose said parts, the surgeons who reimagine the parts, and the scientists who dare to ask wild questions, such as whether a human pancreas can be grown in a pig. Roach's journey through the operating rooms, transplant labs, and burn units of the world is a tour de force of medical ingenuity and ethical introspection. She doesn't just dissect the science; she probes the soul of it.

One example is Roach's exploration of *intestinal vaginoplasty*, a surgical procedure that uses part of the ascending colon to build a vaginal canal in gender-affirming surgery. Roach sits down with urologist Maurice Garcia over pasta and Chianti to discuss the surgical repurposing of the colon. Roach sets the scene:

> I've reserved table 12, a cozy corner two-top where most other patrons can't see or hear you, and the banquette is just long enough for two people to squeeze in side by side. It's the table for canoodlers, or people having an unrestrained conversation about surgically fashioning a vagina out of the colon. The banquette is good, because later my date, Maurice Garcia, will be coming to sit beside me with his iPad, so he can show me a video of the surgery carried out across the street at Cedars-Sinai Medical Center. Dinner and a movie.



CDC/GHO/Mary Hilpertshauser/Wikimedia Commons

Artificial respirators known as iron lungs were used in the 1950s for patients with polio. In severe cases of the disease, paralytic polio could paralyze the diaphragm and rib cage muscles, preventing an individual from breathing. The iron lung used machine-powered negative pressure ventilation to help the body breathe. Outside the machine was a large syringe that drew out air: The reduced pressure inside caused the lungs to expand and take in air, and then when the plunger was pushed, it would then cause the lungs to deflate. This is in contrast to today's ventilators, which use positive pressure to inflate the lungs.

Yet beneath the humor lies a profound respect for the trans women seeking anatomical affirmation and for the surgeons striving to make it happen. The patients detailed in the book are not merely case studies or bodies; they are people with stories.

Throughout the book, Roach is unafraid to ask the awkward questions: Can a finger become a penis? (Yes, it happens in Georgia—the country, not the state.) Is it ethical to grow human organs in pigs? Roach explores the ethical minefield: What if a pig engineered to grow a human organ also ends up with enough human brain cells to foster self-awareness? At what point would different moral standards apply? She delves into ethics surrounding the use of death row prisoners as organ donors in China and the importance of patient autonomy in gender-affirming surgery. Each scenario raises questions that science alone can't answer.

What makes *Replaceable You* so compelling isn't just the remarkable science, but the humanity that Roach uncovers throughout. She introduces us to burn survivors like Diana Tenney, whose story of resilience and recovery is as moving as any medical miracle. Diana survived third-degree burns over 90 percent of her body, endured more than 25 surgeries, and in the process became an advocate and inspiration for burn survivors. Her journey, and her relationship with her husband Jerry, is a testament to the power of support. By telling Diana's story, Roach reminds us that behind every transplant, every prosthetic, every printed organ there's a person hoping to reclaim a piece of themselves.

Roach reminds us that behind every transplant, every prosthetic, every printed organ, there's a person hoping to reclaim a piece of themselves.

Roach also excels at making complex science accessible and even entertaining. Her chapter on skin grafts to treat burn victims includes a comparison to shawarma slicing:

> The skin here is about to be allografted . . . [The doctor] prepares the site with a longish blade called the Goulian (pronounced, with some aptness, *ghoul-ian*). Strips of flesh are pared with a quick, truncated back-and-forth motion. *Where have I seen that*, I think. A moment later, it pops to mind: shawarma shop.

And on ECMO patients—people on life support using a process called extracorporeal membrane oxygenation that can provide oxygen to circulating blood when the heart and lungs cannot—she notes that a patient "can do it without ever taking a breath. If they felt like it, they could watch Netflix with their head underwater." It's anatomy with a wink, but never at the expense of empathy.

Despite her witty writing, Roach also explores serious issues. Ethics are the connective tissue of this book and woven throughout the chapters. She doesn't shy away from the moral murkiness of xenotransplantation, chimerism, or the historical use of death row prisoners as organ donors. In the context of gender-affirming surgery, she highlights the importance of listening to patients and respecting their decisions, especially in a field where innovation and identity intersect.

Replaceable You is a love letter to the adaptability of the human body. It's a celebration of the surgeons who see possibility in scar tissue, the researchers who dream in stem cells, and the patients who endure with grace and grit. Whether you're a biologist, a bioethicist, or just someone who's ever stubbed a toe and then wondered why toes stick out so much anyway, this book will leave you marveling at the meat machine we call home. It's a reminder that regenerative medicine and the science behind it isn't just about fixing what's broken; it's about understanding what it means to be whole.

Jason M. Organ is a professor of anatomy, cell biology, and physiology at Indiana University School of Medicine. His work explores how anatomy is taught, learned, and communicated, in the classroom and beyond. As editor in chief of Anatomical Sciences Education *and as cohost of the* Science Night *podcast, he champions clear, engaging science communication and enjoys translating complex anatomical ideas into something the public might want to hear about—sometimes even on purpose.*

November–December 2025 Volume 34 Number 06

Sigma Xi Today

A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

Sigma Xi Elections Begin November 3

Active Sigma Xi members will receive a ballot from **elections@vote-now.com** to begin voting in the 2025 Sigma Xi elections. All members who receive a ballot can vote for the president-elect, as well as for other open positions in their chapter's region and constituency. Members who aren't affiliated with a chapter can vote for candidates in the Membership-at-Large Constituency Group. Ballots will be personalized with the candidates who pertain to each member.

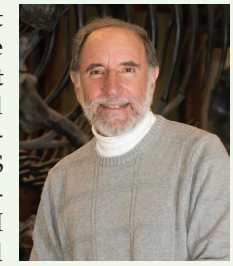
- **President-Elect** — Three-year term beginning July 1, 2026: the first year as president-elect, the second year as president, and the third year as immediate past president.
- **Directors** — Three-year term beginning July 1, 2026. Director positions up for election serve the Mid-Atlantic Region, Northeast Region, Membership-at-Large Constituency Group, and Research and Doctoral Universities Constituency Group.
- **Associate Directors** — Three-year term beginning July 1, 2026. Associate Director positions up for election serve Area Groups, Industries, State & Federal Labs Constituency Group; Comprehensive Colleges & Universities Constituency Group; Southeast Region; and Northwest Region.
- **Representatives on the Committee on Nominations** — Three-year term beginning immediately after the election. Representative positions up for election serve the Canadian/International Constituency Group, Baccalaureate Colleges Constituency Group, North Central Region, and Southwest Region.

Visit **sigmaxi.org** *to learn more about the 2025 election candidates and position responsibilities.*

Sigma Xi Today is managed by Jason Papagan and designed by Chao Hui Tu.

From the President

Inspiring the Next Generation



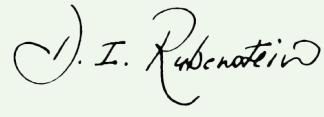
Back in the 1960s, the United States created "alphabet soup" curricula to improve scientific literacy and the nation's technological competitiveness. The Soviet Union had just launched Sputnik, and the United States saw the urgency of educating our next generation of scientists. Hence, new curricula like BSCS (biology), CHEMS (chemistry), and PSSC (physics) were established. This was 60 years ago, but I remember it well. It sparked my interest in science and launched my career!

During graduate school, I worked to expand the study of animal behavior by helping create the field of behavioral ecology. We quantified natural history, modeled animal decision-making using game theory, and tested our models via manipulative experiments, all to help unravel how the environment shapes behavior.

Given that the U.S. government is now suppressing any scientific endeavor that does not support its political or economic interests, many scientists of my generation feel that we are at another "Sputnik moment," one not created by an outside threat, but from within. When Sputnik was launched, President Eisenhower signed the National Defense Education Act, and the NSF and NIH sprang into action to create the aforementioned curricula, the benefits of which are now crystal clear. Today, sadly, no top-down action is likely to rescue science and maintain the pipeline of talented youngsters. Instead, the challenge must be met with bottom-up action. And this is where Sigma Xi and its members must play a leadership role.

It begins with our virtual conference, the 2025 International Forum on Research Excellence (IFoRE). With the theme of "Science and Society: Crafting a Vision for a Sustainable Tomorrow," IFoRE '25 will welcome hundreds of STEM students presenting their research and sharing their vision of what a sustainable tomorrow looks like.

Furthermore, because Sigma Xi is a network of chapters, we should seek to expand the Society's ability to advance the imagination of Next Gens worldwide. When I was president of the Princeton Chapter, I worked with Rush Holt—then deputy director of the university's Plasma Physics Lab and later U.S. Representative—to create the Science Advisors Program. We collaborated with science directors from local pharmaceutical companies and superintendents of local schools to implement hands-on science kits that encouraged thinking, hypothesis generation, and testing of predictions at all grade levels. It made a difference. Given that today's students have not performed well in science on the recent Nation's Report Card, it is time for Sigma Xi scientists to get involved again. Challenge your chapters to inspire, mentor, and nurture young minds to solve the scientific problems confronting society today.



Daniel Rubenstein

From the Lab to Lindau: Sigma Xi Student Member Meg Shieh Attends Exclusive Nobel Laureate Meeting

Back in the fall of 2024, Brown University PhD student Meg Shieh applied to represent Sigma Xi as a student fellow at the 74th Lindau Nobel Laureate Meeting in Lindau, Germany. The annual gathering brings together Nobel Prize–winning scientists with the next generation of researchers, offering unparalleled opportunities for mentorship, collaboration, and inspiration.

Shieh was selected in early 2025 and attended the prestigious event this past July. She joined fellow young scientists from around the world, representing diverse disciplines in the natural sciences. Over the course of the week, she engaged in opportunities to connect with 33 Nobel laureates through lectures, small group discussions, and personal conversations, gaining insights into both groundbreaking scientific research and the human stories behind it. We recently caught up with Meg to hear about her experience at the six-day event.

What motivated you to apply for Sigma Xi's Lindau Nobel Laureate Meetings Fellowship?

I'm currently a fifth year PhD candidate in chemistry at Brown University. My research focuses on developing chemical tools and methods to study reactive sulfur species that play critical regulatory roles in human health and disease. In learning that this year's Lindau Meeting carried a chemistry focus, I remembered seeing a news article on the Sigma Xi site about the two students Sigma Xi sent to Lindau in 2024. Coincidentally, I had just been nominated to be a full member of Sigma Xi the previous year.

What was it like to meet and interact with Nobel laureates in person?

It was so cool! We rubbed elbows with Nobel laureates at breakfast and lunch, and we danced with them during evening festivities. They are absolutely brilliant researchers, but they are also actual people. Sounds like common sense, but the feeling was so different! As an example, we talked about AI with John Jumper, but while sitting in a crowd with him waiting for a science diplomacy panel to begin, a few of us had a wonderful discussion with him about the scientific specifics of obtaining the perfect espresso shot.

Was there a particular Nobel laureate whose talk or advice resonated deeply with you?

I can't pick just one! Martin Chalfie and Morten Meldal told us stories about serendipitous discoveries. Martin also gave us tips on best practices for applying to postdoc positions. Frances Arnold explained how she set up her lab's mentoring system and encouraged us to think outside the box. Steven Chu emphasized the importance of honest communication.

How did the peer atmosphere of young researchers from around the world influence your experience?

It was incredible to meet hundreds of other young scientists from different backgrounds. We had so many dynamic conversations about life (and science, of course). I've come away from this meeting inspired, buzzing with excitement, and with so many new ideas and friendships.

How has attending the Lindau Meeting shaped your perspective on your own research?

It really highlighted to me how my research (and the research of others) is like a puzzle piece. Individually, it might be interesting. But by connecting and collaborating, we can piece together the individual parts to form a greater puzzle.

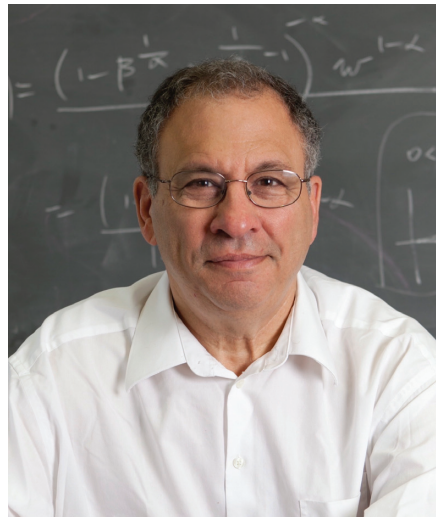
What other interesting details would you like to share about the experience?

When I started my graduate career, I heard that conferences were like summer camp for nerds. If that's true, then the Lindau Meeting was like nerd camp on steroids. Case in point, there was nothing short of a chaotic and disorderly mad dash and grab the first time we heard the conference organizers utter the words "free books." I feel incredibly lucky and deeply honored to have represented Sigma Xi at the Lindau Nobel Laureate Meeting. As cheesy as it sounds, I believe that the connections and friendships I made in just that one week will indeed last forever. I have so many wonderful new friends whom I never would have met otherwise. We're already talking about reunions!

2025 Gold Key Awards

Sigma Xi is pleased to announce that Princeton University's Simon A. Levin and Harvard University's Jennifer A. Lewis have been named as 2025 Gold Key Award recipients. As the Society's highest honor, the Gold Key Award is presented to a Sigma Xi member who has made extraordinary contributions to their profession and fostered critical innovations to enhance the health of the research enterprise. This year's recipients have demonstrated a career-long dedication to cultivating integrity in research and promoting the public understanding of science for the purpose of improving the human condition.

Simon Levin is the James S. McDonnell Distinguished University Professor in Ecology and Evolutionary Biology at Princeton. He is especially noted for his contributions to the development of the foundations of spatial ecology and his work on pattern and scale. More recently, his research has focused on the interface between ecology and economics, especially problems of public goods, common pool resources, and the global commons.



Simon Levin

Jennifer Lewis is the Hansjörg Wyss Professor of Biologically Inspired Engineering at Harvard's John A. Paulson School of Engineering and Applied Sciences, and a core faculty member at the Wyss Institute for Biologically Inspired Engineering. She has made pioneering contributions to the programmable assembly of soft functional, structural, and biological materials. Along with her research team, she has recently developed a multi-material 3D bioprinting method that enables the creation of thick vascularized tissues and 3D organs-on-chip.

Jennifer Lewis

Previous recipients of the award include Cato Laurencin, Shirley M. Tilghman, Bruce Alberts, Shirley M. Malcom, Walter E. Massey, Gordon E. Moore, and Norman R. Augustine.

Freeman Hrabowski to Receive 2025 John P. McGovern Science and Society Award

Sigma Xi is pleased to announce that Freeman A. Hrabowski III has been selected as the 2025 recipient of the John P. McGovern Science and Society Award. This prestigious award honors individuals who have made significant contributions at the intersection of science and society. Dr. Hrabowski is being recognized for his work championing initiatives in leadership development, workforce advancement, civic engagement, and STEM education, with a strong focus on increasing minority participation and success in the fields of science and mathematics.

As president emeritus of the University of Maryland, Baltimore County (UMBC), Dr. Hrabowski is internationally recognized for his transformative leadership in higher education, particularly in advancing diversity and excellence in STEM. Through his vision and commitment, he has inspired generations of students and scholars, reshaping the landscape of STEM education and access. His impact extends well beyond academia, influencing public policy and advancing the broader dialogue on equity and innovation in research.

In 2012, President Barack Obama named him chair of the President's Advisory Commission on Educational Excellence for African Americans.

Since 1984, the McGovern Award has recognized achievements by a scientist or engineer that transcends their career as a researcher. Past recipients include Peter Hotez, Rory Cooper, Sylvia Earle, Kathryn Sullivan, and Condoleezza Rice.

FACES of GIAR: Cass Dedert

Grant: $1,000 in Fall 2022
Education level at time of the grant: PhD student

Project Description Type II diabetes affects over half a billion individuals worldwide and contributes to neurodegenerative disease, and a comprehensive treatment remains elusive. My project focused on the protective role of a secreted neuropeptide called progranulin, which our lab has shown to protect against diabetic pathology, and it explored what signaling pathways might be involved. I found that activation of the kinase glycogen synthase kinase 3 beta (GSK3β) occurs with progranulin treatment, and that inhibiting GSK3β prevents many of its protective effects in neurons under diabetic stress. With the help of this funding from Sigma Xi, I was able to complete the necessary experiments to demonstrate our findings, which have been disseminated through a peer-reviewed manuscript publication and several conference presentations.

How did the grant process or the project itself influence you as a scientist/researcher? This project provided an opportunity for me to gain experience with developing and implementing a novel and impactful research plan at all steps of the research process. The grant-writing process gave me experience with preparing funding proposals, both in writing and in presentation of preliminary data. This experience has also helped me secure future grant funding from other sources and has given me a greater appreciation of the effort that goes into funding a research lab.

What advice would you give to future applicants? Write early and write often! So much of what we do as researchers is communicate our findings, and to do that effectively requires regular practice and feedback. Strong writing pays off immensely and helps to separate you from all the other applicants.

Where are you now? I am currently working as a Research Project Manager at Eyesciences, a Toronto-based startup focused on the development of novel therapeutics for ocular diseases.

Students may apply for Sigma Xi research grants by March 15 and October 1 annually at **sigmaxi.org/giar**

Sigma Xi Hosts 2025 Science Policy Boot Camp

Three teams of students and early-career professionals were awarded prizes at Sigma Xi's fourth annual Science Policy Boot Camp, held July 22–25 at Sigma Xi's Research Triangle Park headquarters. Participants took part in the four-day immersive camp focusing on state-level science policy. The final day featured a "hack-a-thon" competition in which participants formed teams to put new tools and knowledge into action by developing and presenting a real-world science policy solution.

The event featured networking, government tours, and interactive workshops with practitioners and leading experts in science policy. The winning team of Natalie Schulte and Katy Beatty received the $500 top prize for their presentation, "SwineReg Solutions."

2025 Science Policy Bootcamp Winners:
First Prize—$500
"SwineReg Solutions"
Natalie Schulte, Katy Beatty

Second Prize—$250
"The Tempest League"
Kamya Bates, Paula Buchanan, Mariely Vega

Third Prize—$150
"Voices for Resilience"
Hari Balaji, Riley Ragain

People's Choice Award—$150
"The Tempest League"
Kamya Bates, Paula Buchanan, Mariely Vega

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INTERNATIONAL FORUM ON RESEARCH EXCELLENCE

October 30–November 1, 2025

2025 Theme: "SCIENCE AND SOCIETY: CRAFTING A VISION FOR A SUSTAINABLE TOMORROW"

2025 Award Winners

John P. McGovern Science & Society Award

Freeman Hrabowski
The University of Maryland, Baltimore County

William Procter Prize for Scientific Achievement

Alessandro Sette
University of California, San Diego

Walston Chubb Award for Innovation

Richard Spontak
North Carolina State University

Moses and Dorothy Passer Award

Meghan Barrett
Indiana University, Indianapolis

Dr. Lawrence M. Kushner Memorial Award

Ryota Tamura
Keio University School of Medicine, Japan

Dr. Philip Wyatt Technology Transfer Award

Santiago Perez Lloret
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Spirituality Meets Artistry

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"I never expected it to be so beautiful that it takes your breath away."

— Kaya C., on Stauer Opals

In a quaint village, nestled between rolling hills, lived a young woman with a deep appreciation for gemstones. Her grandmother gifted her a delicate cross pendant adorned with opals. The opals shimmered with a mesmerizing play of colors, reflecting hues of blues, greens, and fiery oranges. Her grandmother shared the legend of the opals, believed to bring hope, purity, and luck to those who wore them.

Using this story as inspiration, Stauer brings you the **Opal Spirit Cross Pendant.** With over 2 total carats of Kyocera lab-created opals set in .925 sterling silver encased in yellow gold, this pendant is a radiant celebration of beauty and craftsmanship. Each opal captivates with a kaleidoscopic dance of fiery oranges blending into oceanic blues, streaked with flashes of vibrant green that seem to come alive with every movement. The shimmering opals are skillfully arranged to create an enchanting, otherworldly glow, embodying the spirit of hope and harmony.

This breathtaking combination of color and craftsmanship is available as a limited availability of only 930 pieces, making it a rare and treasured addition to your jewelry collection. Plus, when you order today, you'll receive the **Opal Spirit Cross Pendant at an impossible price of just $59 normally ~~$149~~!**

Don't miss your chance to own this exclusive tribute to timeless elegance and meaningful symbolism.

Jewelry Specifications:

- Pendant: 2 ½ ctw. Kyocera lab opals and Diamond*Aura*® accents. Yellow gold-finished .925 sterling silver setting
- Chain: 18" gold-clad .925 sterling silver chain

Opal Spirit Cross Collection

A. Pendant (2½ ctw)	~~$149~~ $59*	+ S&P	*Save $90*
B. 18" Gold Clad Chain	$59*	+ S&P	
Pendant and Chain	~~$208~~ $79*	+ S&P	*Best Offer!*

**Special price only for customers using the offer code.*

1-800-333-2045

Your Insider Offer Code: OCR247-02

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