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Features

Scientists have scarcely begun studying pristine material from asteroid Bennu that was brought back to Earth by the OSIRIS-REx mission, but they have already found several surprises

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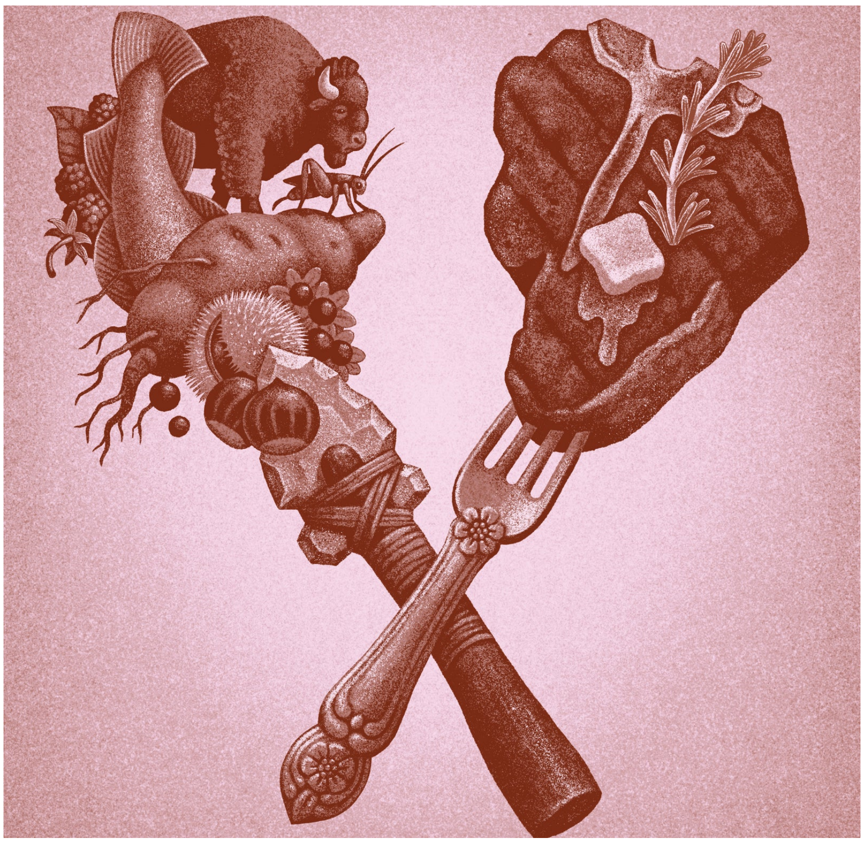
To Follow the Real Early Human Diet, Eat Everything

Nutrition influencers claim we should eat meat-heavy diets like our ancestors did. But our ancestors didn't actually eat that way

By Kate Wong



Miriam Martincic

Paul Saladino is stripped to the waist, biceps bulging as he works a butcher's saw back and forth across a cow femur. When he finally severs the bone, a crowd of onlookers erupts in cheers. Flashing a smile, he checks to make sure he's being filmed, then scoops a spoonful of marrow from the center of one piece of bone. He then deposits it in the mouth of an eager young woman like a priest giving communion.

Saladino, a medical doctor, is a popular proponent of an animal-based diet that exalts meat and organs and demonizes vegetables. Through videos like this one on TikTok, as well as the podcast he hosts, he preaches the value of eating beef and liver, marrow and testicles to millions of followers on social media. He is the author of the 2020 book *The Carnivore Code* and a companion cookbook. He founded the company Heart and Soil, which sells organ-based supplements, and co-founded Lineage Provisions, which sells protein powder and meat sticks. Saladino contends that the traditional food pyramid, with its broad base of plant foods that narrows into animal foods, is upside down and that the medical establishment's view that high cholesterol causes heart disease is wrong. He says that meat and organs are the key to health, strength and vitality.

Saladino is not alone in his carnivorous pursuits. TikTok, Instagram and YouTube are teeming with influencers peddling meat-centric menus. Like the so-called paleo or caveman diets before them, these diets shun ultraprocessed foods such as potato chips, breakfast cereals, packaged breads, sodas and hot dogs. But they are significantly more restrictive than the paleo diet where plant foods are concerned. Some advocates, Saladino and celebrity adventurer Bear Grylls among them, allow for a limited amount of fruit but discourage vegetables, which they contend are loaded with defensive chemicals that are toxic to humans. Others, such as Canadian psychologist Jordan Peterson and his podcast host daughter, Mikhaila, champion a diet of beef, salt and water alone. Many, like social media personality Brian Johnson, aka Liver King, recommend consuming animal products—including dairy and eggs—raw.

On supporting science journalism

Meatfluencers, as they are known, often characterize their regimens as “ancestral,” made up of the foods our ancient predecessors ate. If this is what our ancestors ate, they argue, then this is what the human body is supposed to consume. “If you align your diet and lifestyle with millions of years of human and hominid evolution,” Saladino says in another TikTok appearance, “that is how humans thrive.”

Studies of the remains of our forebears, as well as observations of living primates and modern-day hunter-gatherers, refute the idea that humans evolved to subsist primarily on animals. Meat did play a significant role in our evolution. Yet that doesn’t mean we’re meant to eat like lions. Real ancestral human diets are difficult to reconstruct precisely, but they were vastly more varied than the mostly meat diets of carnivores, a finding that has important implications for what people today should eat to be healthy.

To be fair to the promoters of flesh-forward diets, scientists have traditionally paid a lot of attention to meat eating in human evolution, as have journalists who write about our origins (including me). Several factors have contributed to this trend. For one thing, we humans are unique among primates in regularly hunting animals that are as large as or larger than ourselves, and scientists are particularly interested in understanding traits that set us apart from other creatures. For another, stone tools and butchered animal bones are more readily preserved in the archaeological record than fragile plant remains. And then there’s the fact that the hunting of animals—particularly large, dangerous mammals such as elephants—is inherently more exciting than the quiet business of gathering berries, nuts and tubers. In any case, it doesn't take a lot of googling to turn up a heap of scientific papers and popular articles touting the idea that hunting and eating meat made us human.

Interest in the role of meat and hunting in human origins has deep roots. Charles Darwin even speculated about its importance in his 1871 treatise, *The Descent of Man, and Selection in Relation to Sex*. Ideas about how carnivory shaped human evolution have shifted over the years, but the prevailing wisdom is this: around two million years ago *Homo erectus*, an early member of our genus, began evolving modern human body proportions, with longer legs, shorter arms, a smaller gut and a larger brain. The earliest stone tools and animal bones bearing cut marks date to before that period. The timing suggests that the invention of sharp-edged stone tools allowed early humans to butcher large animals and have access to a rich new source of calories. This nutritious food required less processing in the gastrointestinal tract, which allowed our energetically expensive gut tissue to shrink. Calorie-dense meat also provided fuel that allowed our energetically expensive brains to expand. A feedback loop took hold: as brains ballooned, our increasingly clever ancestors dreamed up ever more effective tools for procuring energy-rich animal foods, fueling more brain growth in *Homo*.

Humans evolved to eat a variety of foods, not just meat. Versatility has been the secret of our success.
Bill O'Leary/The Washington Post via Getty Images

If that were all we knew about human evolution, it'd be tempting to conclude that we evolved to eat a meat-based diet. But that's only a piece of what anthropologists and archaeologists have learned about food and human origins, and even that chapter of our story has undergone revision over the past 15 years in light of new evidence. Fresh fossil discoveries and novel DNA analyses are revealing what our ancestors ate in unprecedented detail. For a clearer understanding of the evolution of humans and our diet, we need to take a closer look at what happened before and after that two-million-year mark.

Let's start at the beginning. Humans, monkeys and apes make up a subset of primates known as the higher primates, which evolved to eat fruit. The hominin lineage (*Homo sapiens* and its extinct relatives, including *Ardipithecus, Australopithecus,* and others) dates to roughly six million to seven million years ago. Fossils of the earliest known hominins indicate that they walked upright on two legs but still spent a lot of time in trees. They don't appear to have made stone tools and probably subsisted on a diet similar to that of chimpanzees and bonobos, our closest living relatives—which is to say mostly fruits, nuts, seeds, roots, flowers and leaves, along with insects and the occasional small mammal.

For the entire first half of our known history, hominins seem to have maintained this plant-based diet—they left no material trace of meat eating. It's not until nearly three million years after our lineage got its start that there's any evidence that they exploited large animals for food.

The oldest possible evidence of meat eating by hominins comes from Dikika, Ethiopia. There researchers found fragments of bone from goat- and cow-size mammals bearing marks suggestive of butchery that occurred at least 3.39 million years ago. The butcher, in this case, was probably *Australopithecus afarensis*, the small-brained, small-bodied hominin species to which the famous Lucy fossil belongs—the only hominin species known from this time and place. Although no tools were discovered, based on the pattern of damage to the bones, the researchers concluded that *A. afarensis* used sharp-edged stones to strip flesh from the bones and struck the bones with blunt stones to access the marrow inside.

The oldest stone tools come from the site of Lomekwi in northwest Kenya. Like the cut-marked bones from Dikika, these 3.3-million-year-old implements significantly predate the origin of our genus, *Homo*, and seem instead to be the handiwork of the small-brained australopiths. Both occurrences also appear to be isolated in time, a flash in the evolutionary pan, separated by the next oldest evidence for stone tools and butchery by hundreds of thousands of years.

It's only after two million years ago that hominins started to incorporate large game into their diet more routinely, according to Briana Pobiner, a paleoanthropologist at the Smithsonian National Museum of Natural History, who studies the evolution of meat eating in humans. The site of Kanjera South in southwestern Kenya, which records hominin activities from around two million years ago, is one of the earliest sites to preserve evidence of what researchers call persistent carnivory. There early members of *Homo* transported choice rocks from as many as 10 kilometers away to make their stone tools. They used these tools to extract meat and marrow from a variety of mammals that lived in the surrounding grasslands, from small antelopes to bovids the size of wildebeests. Some of the antelopes appear to have been acquired intact, presumably through hunting. The larger animals may have been scavenged. However they procured the carcasses, the Kanjera hominins butchered animals at this site repeatedly, over generations, the bones spanning a sediment layer three meters thick.

The hominins at Kanjera went back to this place again and again to butcher animals, but their pattern of persistent carnivory was not widespread elsewhere. Nor was it followed by a steady increase in meat eating over time, as would be expected in the feedback-loop scenario. W. Andrew Barr of George Washington University and his colleagues, including Pobiner, analyzed the evidence for hominin meat consumption in the zooarchaeological record of eastern Africa from between 2.6 million and 1.2 million years ago. Although the evidence for meat eating increases shortly after two million years ago with the debut of *H. erectus*, the first hominin to attain modern body proportions, the study found that this pattern is the result of a sampling bias: researchers have simply collected more archaeological material from this time period than from earlier intervals. Their findings, Barr, Pobiner and their co-authors concluded, did not support the hypothesis that meat made us human.

“When I think about changes in diet over time, I don’t think the change was linear,” Pobiner says. In many ways, the changes have been more about broadening the diet rather than progressing from vegetarian to meat eater, she explains. “Humans are omnivores,” she says. “We’ve always been omnivores.”

Even at Kanjera, with its impressive accumulation of butchered bones, meat wasn’t the only food on offer. Analyses of the cutting edges of a sample of stone tools from the site revealed that most of the implements exhibit wear patterns characteristic of tools that have been used in experiments to chop herbaceous plants and their underground storage organs—those tubers, bulbs, roots and rhizomes that plants produce to store carbohydrates. A smaller proportion showed signs of animal-tissue processing.

As much as the evolution of meat eating is a focus of her work, Pobiner says, “that doesn’t mean that I think that it was ever the most significant component of early human diets.”

It’s possible that early humans were targeting fat rather than meat when they first started butchering animals. Jessica Thompson of Yale University and her colleagues argue that before hominins invented stone tools suitable for hunting large animals, they may have used simpler implements to scavenge abandoned carcasses for their nutritious marrow and brains. Lean meat such as that from wild animals is energetically expensive to metabolize, and in the absence of fat in the diet, it can cause protein poisoning and other ills. Smashing scavenged bones to get to the marrow could have produced the extra nutrients needed to fuel brain growth before our ancestors developed the more complex technology needed for hunting.

The fat and meat of terrestrial mammals weren't the only possible source of extra calories for hungry hominins. Fish, shellfish, and other aquatic animals and plants sustained our forebears who lived near rivers, lakes and oceans. As early as 1.95 million years ago, *Homo* was exploiting fish and turtles, among other aquatic foods, in Kenya's Turkana Basin.

Our ancestors may have also wrung more calories from plant and animal foods by cooking them. Richard Wrangham of Harvard University has proposed that cooking, which makes food easier to chew and digest, may have provided *Homo* with the extra fuel needed to power a bigger brain. In 2022 researchers announced that they had found remains of fish that may have been cooked with controlled heat 780,000 years ago at the site of Gesher Benot Ya'aqov in Israel.

There is another place where scientists can look for clues to what early humans ate: their teeth. When researchers analyzed the tartar preserved in the stained teeth of two *Australopithecus sediba* individuals from South Africa, they found microscopic bits of silica from plants these hominins ate nearly two million years ago, including bark, leaves, sedges and grasses.

Even the Neandertals, our burly cousins who ruled Eurasia for hundreds of thousands of years and are known for having been skilled big-game hunters, consumed plants. Amanda Henry of Leiden University in the Netherlands and her colleagues found traces of legumes, dates and wild barley in the tartar on their fossilized teeth. And researchers led by Karen Hardy of the University of Glasgow discovered roasted starch granules in Neandertal teeth, indicating that they ate cooked vegetables. Some Neandertals might have even forgone animal flesh entirely: in a study co-led by Laura Weyrich of Pennsylvania State University, analyses of DNA preserved in the tartar of Neandertals found in El Sidrón cave in Spain turned up traces of pine nuts, moss and mushrooms—and no meat whatsoever.

Researchers have developed other techniques for studying what hominins put in their mouths and chewed, such as measuring the chemical isotopes in teeth, but these methods have important limitations: they can't determine the proportion of animal versus plant foods in the diet. To that end, another tartar study offers an inkling. James Fellows Yates of the Max Planck Institute for the Science of Human History and his colleagues analyzed DNA from bacteria preserved in Neandertal tartar and compared it with bacterial DNA from the teeth of modern chimps, gorillas, howler monkeys and modern humans. The team found that the Neandertals and modern humans in their sample had a group of *Streptococcus* bacteria in their mouths that the nonhuman primates didn't have. These strep bacteria eat sugars from starchy foods, such as roots, seeds and tubers. Their presence in the mouths of the Neandertals and modern humans—but not the nonhuman primates, which eat mostly nonstarchy plant parts—indicates that *Homo* had adapted to eating an abundance of starchy plant foods by the time Neandertals and modern humans split from their last common ancestor around 600,000 years ago. This timing hints that a high-carb diet helped to power brain expansion in *Homo*.

Other features of teeth suggest additional leads in the quest to understand what our ancestors ate. If you look at hominin tooth morphology over time, says paleoanthropologist and evolutionary biologist Peter Ungar of the University of Arkansas, you see that australopiths had big, flat teeth with thick enamel—traits that indicate they were specialized for crushing hard foods such as seeds. *Homo*, for its part, evolved smaller teeth with crests that were better suited to eating tough foods, including meat. Yet we obviously lack the long, sharp canine teeth that carnivores have for stabbing and tearing at prey and the sharp-edged carnassial teeth for shearing flesh.

“We’re not pure carnivores, we never were,” Ungar says. “Our teeth are not designed for meat eating.” That doesn’t mean we can’t survive on animal tissue, he notes—cutting and cooking both make meat easier for us to consume—but “anybody who’s chewed on beef jerky long enough knows that our teeth really aren’t designed for that. Or, for that matter, raw steak.”

The microscopic pits and scratches that foods leave on the teeth reinforce this message. Whereas *Australopithecus* microwear patterns reflect a narrow range of food types, early *Homo* shows a somewhat wider range. Later members of our genus show microwear texture patterns that indicate they ate even more kinds of foods. Although these lines of evidence are limited, Ungar says, they suggest *Homo* became a more versatile eater, capable of consuming a wider variety of foods than its predecessors. This versatility would have served our ancestors well as they spread into new environments with a greater diversity of food types on offer.

Proponents of animal-based diets are fond of pointing to the Hadza, a group of foragers in northern Tanzania, to make their case for going hard on meat. Saladino and Liver King name-check them regularly in their social media videos. “I can tell you very clearly that the Hadza don’t give a shit about vegetables. They don’t really eat vegetables,” says Saladino, who once visited the Hadza on an excursion set up for tourists.

Anthropologists who have lived with the Hadza and studied their diet for years would disagree. Herman Pontzer of Duke University notes that for decades researchers have observed that plant foods make up at least 50 percent of the Hadza diet. The Hadza are not unique in this regard. Hunter-gatherers around the world get roughly half their calories from plant foods and half from animal foods on average. But that average obscures the real value of the hunting-and-gathering strategy, which is that it allows people to subsist on a wide variety of diets depending on what's available in their environment at a given time of year. Long-term studies of the Hadza show that some months they may get most of their calories from honey; other months they may eat mostly plant foods, including root vegetables. There are times they hardly eat any meat at all.

What made humans so triumphant wasn't that we swapped out plants for animals but that we added hunting to our repertoire. Hunting and gathering reliably produces more calories a day than any other primate strategy, Pontzer says. The reason it works is that it's a mixed portfolio. "You have some people going after high-value, hard-to-get animals with a lot of protein and fat, which is great," he says. "And you have people who are going after more dependable plant foods. It's the balance of those things that makes it so successful."

Hunting and gathering produces so many calories, in fact, that people can afford to share them with other group members, including children, whose brains take longer to develop than in other species and who need more time to learn how to fend for themselves. A strict plant eater can't do that, because although the number of calories one can get every day eating plants is very dependable, it might not be high enough to produce a surfeit of calories. A strict meat eater, on the other hand, will have long periods of famine between feasts that do not, on average, generate extra calories. But when we put those two things together, Pontzer observes, we generate a surplus. And that surplus, he surmises, is the variable that's made energetically expensive human things such as large brains and extended childhood possible.

What the fossil, archaeological and ethnographic evidence indicates, then, is that there is no one diet that nature prescribed for us. What our ancestors ate varied dramatically over time and space, driven in no small part by what was available to them as seasons changed, climate shifted, and populations spread into new ecosystems. Forged in that crucible of uncertainty, we evolved the ability to survive and thrive on an impressive diversity of foods. Hunter-gatherers around the world eat diets with wildly different proportions of plant and animal foods, and all of them appear to be healthy, protected from heart disease, diabetes, and other maladies that are common in industrial populations.

So what is a person looking to eat healthily supposed to do? “I think what it says is you should feel liberated to try a bunch of different diets and find one that works for you,” Pontzer says. But “when somebody tells you that there’s only one way to eat, they are wrong, and you can stop listening.”

Kate Wong is an award-winning science writer and senior editor at *Scientific American* focused on evolution, ecology, anthropology, archaeology, paleontology and animal behavior. She is fascinated by human origins, which she has covered for more than 25 years. Recently she has become obsessed with birds. Her reporting has taken her to caves in France and Croatia that Neandertals once called home, to the shores of Kenya's Lake Turkana in search of the oldest stone tools in the world, to Madagascar on an expedition to unearth ancient mammals and dinosaurs, to the icy waters of Antarctica, where humpback whales feast on krill, and on a "Big Day" race around the state of Connecticut to find as many bird species as possible in 24 hours. Kate is co-author, with Donald Johanson, of *Lucy's Legacy: The Quest for Human Origins*. She holds a bachelor of science degree in biological anthropology and zoology from the University of Michigan. Follow Wong on X (formerly Twitter) @katewong

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People Who Are Fat and Healthy May Hold Keys to Understanding Obesity

“Heavy and healthy” can be a rare or common condition. But either way it may signal that some excess weight is just fine

By Christie Aschwanden

Miriam Martincic

When the 25-year-old woman enrolled in a longitudinal study on obesity in 2016, she was healthy by all standard measures, with one exception: her body mass index (BMI). As is the norm for study participants, her identity is protected, but let’s call her Mary. At 215 pounds, Mary had a BMI—a metric based on height and weight—that put her squarely in the “obese” category. Yet she didn’t have health problems associated with obesity, such as high blood pressure, elevated levels of cholesterol and other blood lipids, or a prediabetic condition called insulin resistance. Five years later Mary had gained 68 pounds, but her vital signs and blood work showed her to be healthy even as her BMI rose enough to categorize her as extremely obese.

Mary is not alone. Although people with more body fat are at increased risk of health conditions such as diabetes, heart disease, stroke and some cancers, studies have repeatedly identified a subset of people with high BMIs and good metabolic health. Their blood pressure, cholesterol levels, insulin sensitivity, triglyceride counts, liver fat levels, and more are good. Researchers call this phenomenon metabolically healthy obesity (MHO). Depending on how it's defined, the condition fits as few as 6 percent or as many as 60 percent of adults classified as obese according to their BMI numbers. (People with BMIs between 25 and 29.9 are considered overweight, and those with values higher than 30 rate as obese.) They are heavy, but they are healthy.

> The identification of people with metabolically healthy obesity suggests obesity may not automatically lead to illness.

The identification of people with MHO suggests—controversially—that obesity may not automatically lead to illness and that the health risks associated with it may be overstated. MHO has been embraced by a movement that says a person can be healthy at any size: patients and physicians who push back against the stigma and stereotyping that society and the medical establishment have attached to people with bigger bodies. It also ties in with mounting criticism of the accuracy and usefulness of BMI as a measure of health. “I’ve found that BMI has not been that helpful in predicting who’s at risk of disease among my patients,” says Mara Gordon, an assistant professor of family medicine at Cooper Medical School of Rowan University in Camden, N.J.

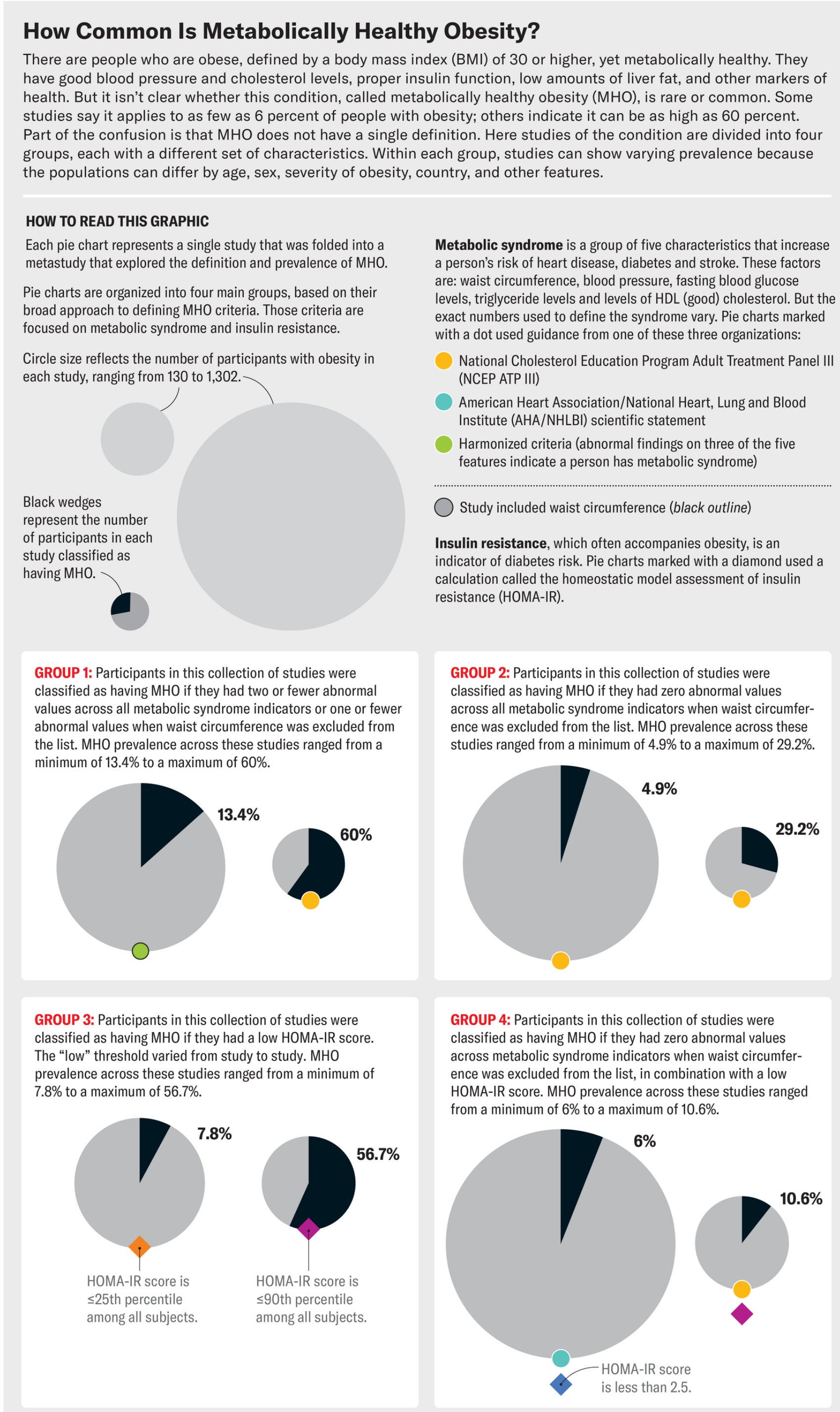
MHO is contentious because it challenges the idea, drawn from many studies and decades of research, that the risk of serious illness rises with obesity. What’s more, losing weight has been shown to improve many conditions, including diabetes, high blood pressure, elevated blood lipids, obstructive sleep apnea and osteoarthritis.

Obesity is “not a cosmetic issue. It’s not about size,” says Alyson Goodman, senior medical officer in the Centers for Disease Control and Prevention’s Division of Nutrition, Physical Activity and Obesity. “We’re worried about the risk for serious chronic diseases over time.” Some researchers contend that MHO is merely a temporary state obese people may pass through on the way to developing health issues commonly connected to a higher body weight.

Still, Mary and others like her are proof that people can be obese but medically healthy for many years. Other research has found that being a bit overweight is not as dangerous as previous guidance suggested and may even be protective. New work on the physiology of fat shows that it’s not always a problem. More and more evidence suggests it’s time to reconsider standard assumptions about weight and health.

Samuel Klein, a physician and obesity expert at Washington University School of Medicine in St. Louis, and his research group have identified people who are obese but seem to be resistant to obesity-related metabolic effects. Klein cautions that “it’s a very small percentage of obese people who are truly metabolically healthy,” but he says it’s a real phenomenon. And his studies aren’t the only ones to find it. People with MHO have been identified in many cohorts, but it’s hard to know how common it really is because different studies have used different criteria for classifying MHO. “There are more than 30 different definitions in the literature,” Klein says, “so it can be really misleading.”

One of the most extensive studies of MHO examined data from NHANES III, a representative survey of more than 12,000 people in the U.S., and determined that MHO was best categorized based on three criteria. One is blood pressure (systolic blood pressure—the first of the two numbers you get when your pressure is measured—less than 130 millimeters of mercury, or mm Hg, without medications). The second is waist-to-hip ratio (less than 0.95 for women and less than 1.03 for men). And the third is the absence of type 2 diabetes. Using these criteria, the researchers calculated that 41 percent of participants in the NHANES III cohort with obesity could be considered as having MHO. The scientists also applied them to people in the UK Biobank database and found that 19 percent of obese participants in that cohort of more than 374,000 people had MHO. Under these criteria, MHO was not associated with any greater risk of death from cardiovascular disease or other causes compared with a “normal weight” group, says the study’s senior author, Matthias Schulze, a molecular epidemiologist at the German Institute of Human Nutrition Potsdam-Rehbrücke in Nuthetal.

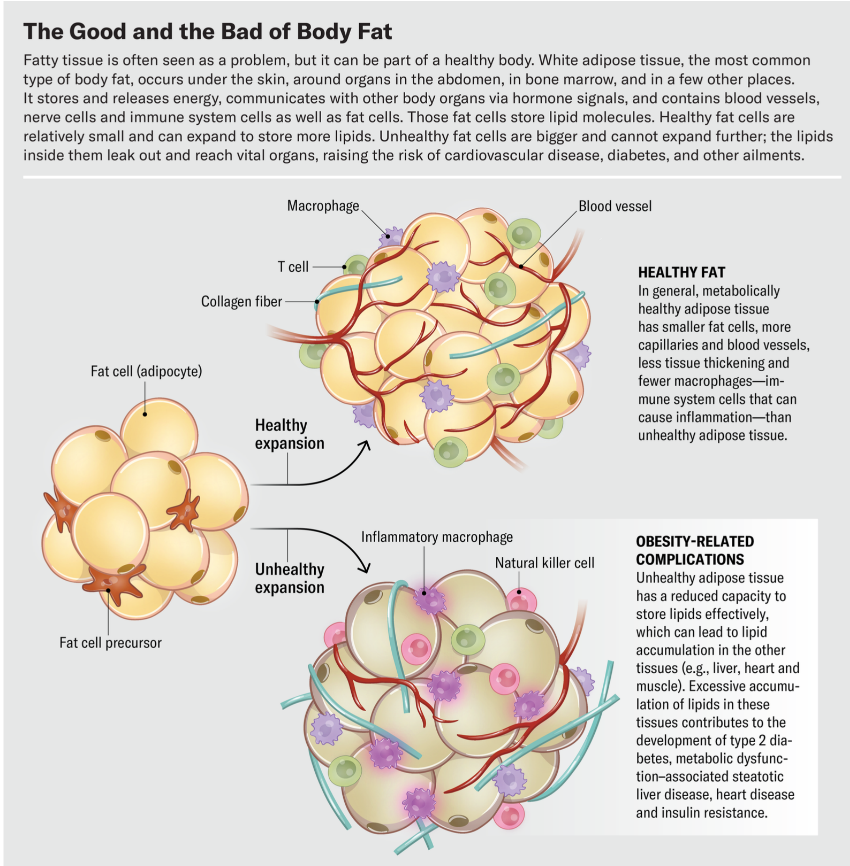


Jen Christiansen; Source: "Metabolically Healthy Obesity: Facts and Fantasies," by Gordon I. Smith, Bettina Mittendorfer and Samuel Klein, in *Journal of Clinical Investigation*, Vol. 129; October 2019 (*data*)

But were all these people truly metabolically healthy? It depends on how you define MHO. Schulze and his colleagues examined three other common definitions and found that less than 6 percent of the NHANES III participants in their study met the criteria for all three, with the range going from just under 10 percent for the strictest definition to nearly 47 percent for a definition that allowed up to two of five possible metabolic symptoms to be present.

Although some people clearly have MHO, researchers disagree about whether it persists or is just a temporary state. A study of more than 4,000 adults in Australia found that about 12 percent of them had MHO, but about a third of those people became metabolically unhealthy over the course of the five- to 10-year follow-up. An analysis of more than 4,000 participants in the long-running Framingham Heart Study found that almost half of people categorized as having MHO at one point in the longitudinal study no longer did by the next examination cycle, four years later. And a study of British government workers over two decades found that slightly more than a third of the study's obese participants had MHO at baseline, but after 10 years, 35 percent of them had stopped meeting the criteria, and after 20 years, 48 percent were no longer healthy enough to be categorized as having MHO. These studies all suggest that MHO doesn't last for everyone. But looked at a different way, the studies also show that a substantial number of obese people—often more than half—maintained metabolic health for many years.

Klein's group has identified people who, like Mary, fit the most stringent definitions of MHO and appear to resist the adverse effects of weight gain and higher body fat percentage on their cardiovascular and metabolic systems over time. Researchers are eager to understand exactly what it is that protects them.



Ni-ka Ford; Sources: "Adipose Tissue Dysfunction as Determinant of Obesity-Associated Metabolic Complications," by Michele Longo et al., in *International Journal of Molecular Sciences*, Vol. 20; May 2019, and "Targeting Adipose Tissue in the Treatment of Obesity-Associated Diabetes," by Christine M. Kusminski et al., in *Nature Reviews Drug Discovery*, Vol. 15; June 2016 (*references*); Jeffrey Horowitz (*consultant*)

There are some clues. People with MHO are typically women who carry their fat mainly in their buttocks and hips while having a narrow waist, Klein says. Their fat tissue seems to function in a way that's protective. Their bodies are sensitive to insulin. Compared with people with metabolically unhealthy obesity, they have higher levels of physical fitness and lower body fat percentages. Ethnic background also matters. People of South Asian, East Asian, Chinese or Japanese descent tend to have metabolic complications at a lower BMI or body weight than people of other ancestries, Klein says.

How fat is stored in the body may explain some of these findings. Excess lipids can collect in internal organs and disrupt their functioning—a phenomenon known as lipotoxicity, says Daniel Cuthbertson, a physician in cardiovascular and metabolic medicine and a professor at the University of Liverpool in England. This fat can induce insulin resistance, or it may incite chronic inflammation or scarring in the organs. “A small amount of fat deposition within the liver and a small amount within the pancreas can make a huge difference to someone’s metabolic state,” Cuthbertson says. This is true whether the person has obesity or not, he says. People with low BMIs can also have many of the health issues associated with obesity if fat is stored in their organs.

> “The specter of death is always presented to me as a part of my health profile because of my body size.” —Tigress Osborn *National Association to Advance Fat Acceptance July/August*

Why some people have health problems and others at a similar weight don’t may be explained by something called a personal fat threshold—how much fat your body can deposit in subcutaneous fat stores (the fat right underneath your skin) before it moves to sites such as the liver and the pancreas where it causes problems, Cuthbertson says. “Different people have different personal fat thresholds,” he says. People with South Asian ancestry, he says, “probably have a lower personal fat threshold because when they gain weight, they don’t need to gain as much weight to develop more severe health consequences.”

“Fat tissue is fantastic,” says Jeffrey Horowitz, a professor at the University of Michigan, who studies exercise and metabolism. It’s a complex mix of different cells intermeshed with a protein matrix, which forms a kind of net that holds the tissue together. The vast majority of our fat is stored subcutaneously, and that’s generally the best place to have it, he says. “If you’re going to be storing fat, you want to be storing it there and not in your visceral region.” Fat in the thighs is better than fat in the belly. One key feature of obese people with metabolic impairment is that they’re no longer able to store fat effectively in subcutaneous regions, so excess amounts go into the circulatory system and cause problems elsewhere. “If you can increase your capacity to store it, that would be great,” Horowitz says. Some drugs that do exactly that—expand subcutaneous fat tissue's storage capacity—can be used to temper the symptoms of diabetes or prediabetes, Horowitz says.

When entering middle age, most healthy, active people gain body fat. But their risk of developing diabetes will be lower if they have small fat cells that can expand effectively and have sufficient vasculature to feed the fatty tissue, Horowitz says. "Some people innately have that capacity," he adds. He likens it to an expandable suitcase that is normally zipped closed but has the ability to expand if you find yourself with extra cargo. Fat tissue in people with MHO seems to be adept at this scale-up.

The recognition that it's possible to be heavy and metabolically healthy may help the push to destigmatize larger bodies and acknowledge that bigger is not bad. "The idea that people are fat because they are lazy and greedy is still pervasive," says Tigress Osborn, executive director of the National Association to Advance Fat Acceptance. The evidence emphatically shows that these biases are false. "Body weight regulation is extremely complex and involves many biological pathways and factors beyond just what we eat or how much we exercise," says Rebecca Puhl, professor of human health and family development at the University of Connecticut. "Many of these factors, like genetics, environment and biology, are outside of personal control," she adds. Yet fatness has become a medical category, Osborn says, rather than just "a physiological difference between people." Instead of recognizing natural variation in body sizes and shapes, we label fatter bodies as diseased, she says.

In medical settings, larger-bodied people are constantly bombarded with the message that their fat is slowly and surely killing them, Osborn says, "even when you are a fat person who has none of the markers [of ill health]." She adds that "the specter of death is always presented to me as a part of my health profile because of my body size, regardless of what my numbers say. At what point do I ever get to be designated as healthy?"

Weight stigma itself is a public health issue, Puhl says. "When a person is shamed, stigmatized, treated unfairly or bullied because of their body size, this increases their level of psychological distress," she explains. It also ups the risk of depression, anxiety, low self-esteem, poor body image, and even suicidal thoughts and risky behaviors such as substance use. Stigma can become a form of chronic stress that can increase cortisol levels and cause physical harm—and weight gain. Studies show that weight discrimination and bias are common in health-care settings, which can discourage heavier people from getting needed medical help. Bias on the part of health-care providers can also interfere with proper diagnoses when doctors assume their patients aren't sick and just need to lose weight, Puhl notes. Repeatedly going on and off diets—yo-yo dieting—can cause major health problems.

Obesity's status as a disease was formalized in a resolution passed in 2013 by the American Medical Association's house of delegates. Douglas Martin, medical director of occupational medicine at CNOS in Dakota Dunes, S.D., chaired the AMA committee that heard testimony on the resolution. There were two main drivers behind the effort, he says. The biggest one was that physicians were having difficulty getting certain tests and treatments for obesity covered by insurance carriers. "You couldn't treat obesity in and of itself. It had to be in concert with diabetes, hypertension, joint problems, etcetera," Martin says. The second driver was a growing concern that obesity was becoming epidemic in the U.S. The most current statistics from the CDC show that nearly 42 percent of adults in the U.S. have BMIs that classify them as obese.

The resolution was adopted, after some vigorous debate. The AMA's Council on Science and Public Health recommended against the measure. "Just being of increased weight, if there's no other impaired function, doesn't fit any of those definitions of a disease," council member Robert Gilchick told MedPage Today at the time. He objected to giving a disease label to apparently healthy people, asking, "Why should a third of Americans be diagnosed with a disease if they're not necessarily sick?" Others on the council worried that people with obesity who improved their diet, physical activity and sleeping habits would still be identified as "diseased" and pressured to get treatment if they failed to change their BMI classification.

Some people in the health field hoped that declaring obesity a disease would reduce stigma in some ways, by conveying the idea that it is a medical condition rather than a personal failing. But Osborn says that the designation has also led to mixed messages. She asserts that "it makes fat people feel like their doctors are blaming them for not treating their disease correctly." Even worse, "we're only going to talk about you as a disease now, and we're only going to talk about your body as a medical condition, as though there are no other aspects to living in the human body."

Turning obesity into a disease essentially meant declaring that larger bodies are abnormal and unwell. To Osborn's question, "At what point do I ever get to be designated as healthy?" the answer from the medical establishment was: never. (Unless you make yourself smaller.)

One major objection raised to declaring obesity a disease is that its basic diagnostic measure may not be meaningful. The standard for measuring obesity is BMI, in part because it is easy to gauge, is inexpensive and, at a population level, correlates well to body fat levels. But it's an imperfect metric. Actor Dwayne "The Rock" Johnson has a BMI of around 34, "but he's not obese—he's a very muscular kind of guy," Klein says. On the other end of the spectrum, he says, "you can have people with a normal BMI who are very doughy, and they have a high body fat percentage." Ideally, obesity should be based on the percentage and location of that fat, Klein says, as well as any medical complication present, "but again, we don't have good cutoffs."

The current system of BMI classification is, in fact, totally arbitrary, says epidemiologist Katherine Flegal. Now a consulting professor at Stanford University, Flegal spent nearly 30 years at the CDC's National Center for Health Statistics. Flegal says the BMI cutoffs for healthy, overweight and obese are not based on solid research. In 2005 she and her colleagues published an analysis of U.S. population statistics showing that people classified as overweight (BMI of 25 to 29.9) actually had lower death rates than people in the "healthy" category. In 2013 she and several collaborators published a review pooling data from 97 studies from around the world, with more than 2.8 million people, that showed the same thing.

Flegal says her work doesn't show that fat is harmless, but it has been attacked by different scientists in this area. And other large studies have contradicted her findings. For instance, in a multistudy analysis published in 2016, researchers examined records from 3.9 million people and found that death rates went up consistently as BMI classifications rose from healthy to severely obese.

All these studies on the link between BMI and mortality—both its pros and its cons—suggest that this entrenched metric does not measure the things that matter most about health and that the relationship between BMI and health is not straightforward. The medical community is beginning to accept this criticism of the ubiquitous measure. In 2023 the AMA adopted a new policy and stated that BMI is "an imperfect way to measure body fat in multiple groups given that it does not account for differences across race/ethnic groups, sexes, genders, and age-span."

The links between weight and health become even more complex when researchers look at weight loss. "We don't really understand why losing weight is so beneficial," Klein says. People with obesity and metabolic problems who lose 5 percent of their body weight often show marked improvements in health measures, and more loss is better up until around 15 to 25 percent of the person's starting weight, where the benefits may max out, Klein says. It's not clear why.

But losing weight does not always improve health. The Look AHEAD study was a large-scale clinical trial that tested whether an intensive, lifestyle-based weight-loss intervention could reduce the incidence of cardiovascular events in overweight or obese adults with type 2 diabetes. The trial, which included more than 5,000 people, was halted early because although the participants receiving the intervention did lose more weight than those in the control group, they did not show a reduction in cardiovascular problems.

Losing fat is no easy task. Many decades' worth of evidence demonstrates that most efforts to lose weight through diet and exercise fail. New drugs such as Ozempic and Wegovy that work by mimicking the hormone GLP-1 (glucagonlike peptide 1) are producing weight loss at levels never before seen from a medication, but they're extremely expensive and in short supply. And some of the people who could benefit the most won't have access, which could make issues of health equity even worse.

When people stop taking these drugs, the weight comes back, so patients may need to be on them for life. The drugs also don't work for everyone, and they come with side effects that could make it hard for some to take them over the long term. All of this means that many people are going to continue living in bodies that are larger than the medical (or social) ideal. Is it possible for them to be healthy in the bodies they have?

The evidence points to a qualified yes. Body weight and shapes exist on a continuum, and the extreme ends of the continuum—being medically very underweight or extremely obese—do seem to come with a high risk of health problems. But there's a lot of variation and nuance.

The British Dietetic Association recently assessed the evidence on BMI and health for a report offering food and nutrition advice for adults aged 65 and older. "One of the pieces of advice is don't worry if you're a bit overweight," says Mary Hickson, a professor of dietetics at the University of Plymouth in England, who was involved in the report. The researchers found that in older adults, the range for healthy weight is wider than assumed: instead of a BMI of 18 to 25, it can be up to 28 or 29. Why the change? "I don't think anybody's really certain," she says. One theory is that fat reserves are beneficial—having a little stored gives you some energy to call on if you get sick.

There's also the fact that body composition changes with age. "When you hit about age 40, you start to very slowly lose lean tissue, which is primarily skeletal muscle," Hickson says. Body composition slowly shifts to less lean and more fat mass, and this change becomes more pronounced in a person's mid-60s and 70s. The studies Hickson's group reviewed showed a connection between being slightly overweight and having lower death rates than underweight groups. "It could be that you're better able to maintain your muscle mass the more weight you carry in your body, because people who are obese do have higher levels of muscle," Hickson says. For these older people, the report's takeaway message was to enjoy eating and not worry too much about being a little overweight.

> Some people do have high levels of fat without health consequences. But it's clear that certain types of fat are detrimental.

But separately from metabolic health, excessive weight can raise certain disease risks as time goes on. People with MHO are still at risk of biomechanical complications from obesity, such as sleep apnea, osteoarthritis, gastroesophageal reflux, urinary incontinence, and other consequences of carrying a large body mass over the years, says W. Timothy Garvey, an endocrinologist at the University of Alabama at Birmingham. “They’re not going to get a free ticket from that perspective.”

Cancer is another danger that comes with all types of obesity. “There’s very good evidence that the risk of probably 15 different cancers is significantly increased,” Cuthbertson says. The mechanisms aren’t clear, but one theory is that it’s driven by hormonal changes associated with obesity. Fat tissue also can secrete biochemical signals that may promote the growth of tumor cells. Another hypothesis is that fat tissue can cause inflammation that may exacerbate cancer.

Dementia is also more common. Dementia risk is increased in people who have insulin resistance, and people who’ve been living with obesity and insulin resistance are at added risk for developing cognitive dysfunction and dementia later in life, Klein says—a condition sometimes called type 3 diabetes.

So where does this leave us? The study of metabolically healthy obesity shows that the relationship between body fat and disease is complicated. Some people really do have high levels of body fat without bad health consequences. But it’s pretty clear that certain types of fat, such as the fat tissue surrounding internal organs, are detrimental. “If you are obese, losing a little bit of weight has significant health benefits,” Klein says.

Yet it’s hard to lose weight, and it’s impossible to target specific places in the body for that weight loss. And given how harmful fat stigma can be, focusing on weight may do more harm than good, says Gordon, the New Jersey physician. Rather than encouraging her patients to conform to an idealized weight or body type, Gordon focuses on things such as blood pressure, insulin resistance and lipid numbers. These conversations, she says, have nothing to do with the number on the bathroom scale. They're about preventing complications from diabetes or joint pain or helping people sleep better. "If a patient has evidence of glucose intolerance, we talk about that. Some of the best ways to prevent diabetes are regular exercise and reducing sugar in the diet. So we talk about that."

JoAnn E. Manson, an endocrinologist and epidemiologist at Harvard Medical School, says that after spending years studying obesity, she has concluded that emphasizing the digits on the scale is not as helpful as working toward a healthy, active lifestyle; instead it can become part of the problem. People who've been told they must lose weight for their health and try unsuccessfully to do so may feel a sense of despair.

Manson says the focus should be not just on pounds but also on all the things we already know we should be doing: eating diets higher in fruits, vegetables and whole grains; engaging in regular physical activity; and spending time outdoors. "If people are following a healthy lifestyle, and they're less preoccupied with a number on the scale, they're also less likely to feel stress and anxiety about their weight," Manson says. Reducing stress and anxiety around body weight issues can in itself contribute to better health.

The latest obesity research offers a hopeful message—that health isn't just about what the scale shows. Feeling comfortable, safe and accepted in one's body is important, too. Health-care providers who treat heavier patients with respect and attention, rather than blaming all their medical issues on weight, can help people of any body size manage their health. Increasing knowledge about the effects of different types of fat, in different locations, may lead to better assessments of what is worrisome and what is not. Being well is about more than your body size. It's about how you care for it.

Christie Aschwanden, a journalist and frequent *Scientific American* contributor, is host of Uncertain, a podcast about uncertainty and science. She is author of *Good to Go: What the Athlete in All of Us*

Can Learn from the Strange Science of Recovery (W. W. Norton, 2019).

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Ozempic Quiets Food Noise in the Brain—But How?

Blockbuster weight-loss drugs are revealing how appetite, pleasure and addiction work in the brain

By Lauren J. Young


Miriam Martincic

Kimberly Chauche, a corporate secretary in Lincoln, Neb., says she's always been overweight. When she was as young as five years old, her doctors started trying to figure out why. Since then her life has involved nutritionists and personal trainers, and eventually she sought therapists to treat her compulsive eating and weight-related anxiety. Yet answers never arrived, and solutions never lasted.

At 43, Chauche was prescribed a weight-loss medication called Wegovy—one of a new class of drugs that mimic a hormone responsible for insulin production. She took her first dose in March 2024, injecting it into herself with a needle. Within a couple of months she had lost almost 20 pounds, and that felt great. But the weight loss seemed like a bonus compared with a startling change in how she reacted to food.

She noticed the shift almost immediately: One day her son was eating popcorn, a snack she could never resist, and she walked right past the bowl. “All of a sudden it was like some part of my brain that was always there just went quiet,” she says. Her eating habits improved, and her anxiety eased. “It felt almost surreal to put an injector against my leg and have happen in 48 hours what decades of intervention could not accomplish,” she says. “If I had lost almost no weight, just to have my brain working the way it’s working, I would stay on this medication forever.”

Chauche is hardly alone in her effusive descriptions of how Wegovy vanquished her intrusive thoughts about food—an experience increasingly referred to as the “quieting of food noise.” Researchers—some of whom ushered in the development of these blockbuster drugs—want to understand why.

Among them is biochemist Svetlana Mojsov of the Rockefeller University, who has spent about 50 years investigating gut hormones that could be key to regulating blood glucose levels. In seeking potential treatments for type 2 diabetes, Mojsov ultimately focused on one hormone: glucagonlike peptide 1, or GLP-1. Her sequence of the protein in the 1980s became the initial template for drugs like Wegovy. The medications, called GLP-1 receptor agonists, use a synthetic version of the natural substance to activate the hormone's receptors. The first ones arrived in 2005. In 2017 the U.S. Food and Drug Administration approved semaglutide—now widely known as Ozempic.

In the years since Ozempic came to market, GLP-1 drugs have catapulted to stardom, becoming a multibillion-dollar industry with a surreal series of successes, first as an effective treatment for diabetes and then as a hit for weight loss. Wegovy, a version of semaglutide specifically for weight loss, became available in 2021. Both drugs were created by Novo Nordisk; other pharmaceutical companies have developed similar ones. One 2024 survey in the U.S. found that one in eight adults reported having taken a GLP-1 drug.

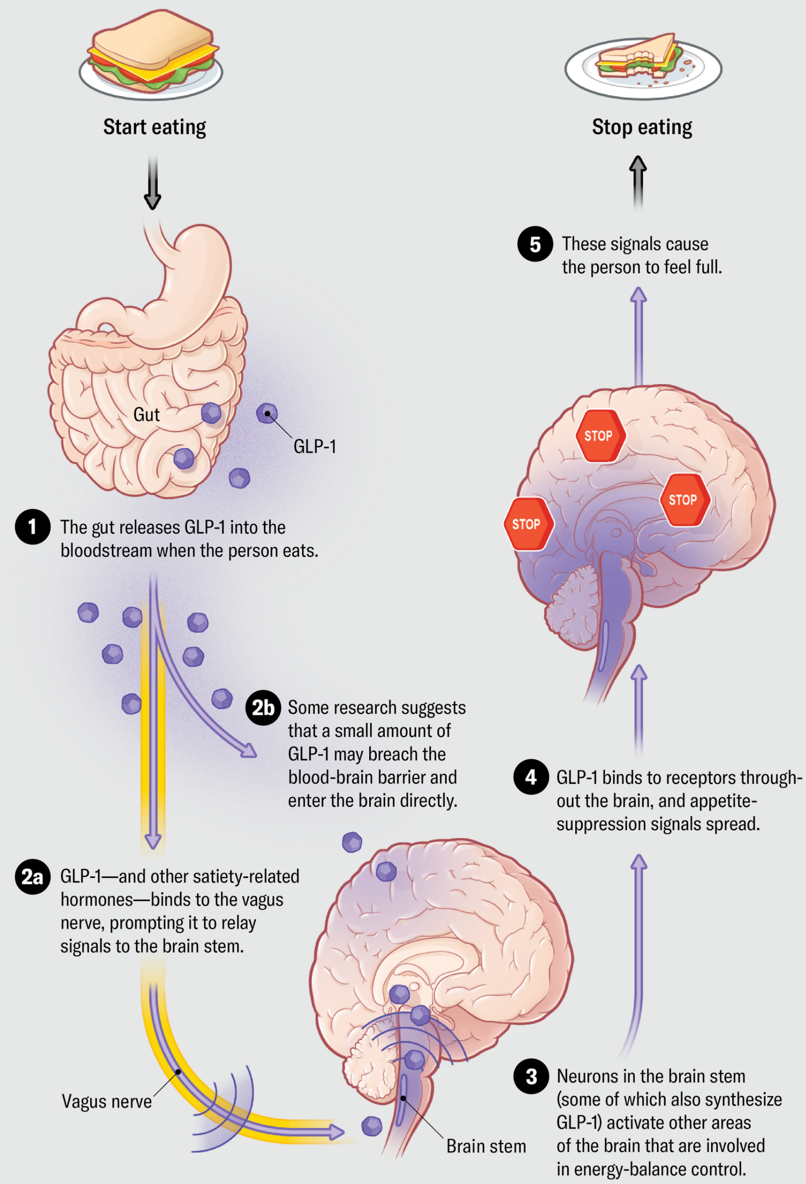
Mojsov and other researchers know that these drugs make people lose weight because they reduce appetite and thus food intake. They make people feel fuller, faster. But scientists don't have a technical definition for so-called food noise, and they are only beginning to understand how synthetic GLP-1 acts not just in the digestive system but in the brain. This work is illuminating neurobiological explanations for hunger and satiety, pleasure and reward—as well as why these sensations so critical to survival might get dysregulated, causing compulsive behaviors and addictive patterns. "That's what we need to understand now," Mojsov says. "The next frontier is to understand the biology behind the Ozempic effects on the brain."

GLP-1 is one of many essential gut hormones that help to control eating behavior, nutritional absorption, digestion, and the overall balance of energy coming into and being used by the body. Over the past few decades several hormones from various body systems involved in food intake have been targeted as potential treatments for obesity and diabetes, but “GLP-1 seems to be the one that’s risen to the top, at least for pharmacotherapy,” says Scott Kanoski, a behavioral neuroscientist and professor at the University of Southern California.

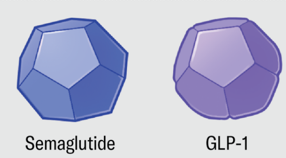
That’s in part because it belongs to a batch of hormones called incretins, which prompt insulin production in response to food ingestion. In a 1987 study, Mojsov and her collaborators injected GLP-1 into a rat pancreas model to see whether it stimulated insulin secretion. “It was a beautifully clear-cut result,” Mojsov says. “As the GLP-1 levels went up, insulin levels went up.”

GLP-1's Role in the Brain

GLP-1 is one of many important hormones produced in the gut in response to eating food. It has two well-established roles in the body: signaling to the pancreas to produce insulin and signaling to the brain to influence satiety and food intake. To communicate with the brain, GLP-1 released from the intestines binds to the vagus nerve—a long cranial nerve that shuttles signals from the gut and other organs to the brain stem. Once it arrives, neurons activate various brain regions, including those that cause people to feel full and stop eating. Researchers have found that neurons in the brain stem also produce GLP-1. Evidence suggests that GLP-1 performs similar roles in the gut and in the brain but in different ways.



HOW DOES OZEMPIC FIT IN?
Ozempic is a drug called semaglutide—a synthetic mimic of GLP-1 with a burlier structure that doesn't break down as easily and lasts far longer in the body. Semaglutide can cause weight loss by causing people to feel full and therefore eat less.



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The basic pathway of GLP-1 in the gut goes like this: When a person eats a meal, a cascade of hormones, including GLP-1, is released to aid food absorption and digestion. As the food gets broken down into glucose and other molecules in the digestive tract, GLP-1 gets released from the intestine. Levels of the hormone rise slowly, then spike to signal fullness.

Some GLP-1 in circulating blood binds directly to receptors in the pancreas to prompt the release of insulin. The hormone also can latch on to receptors on the vagus nerve—a long cranial nerve that shuttles messages between the brain and organs throughout the body. While a person eats, hormonal messages traveling via the vagus nerve tell their pancreas to produce insulin, which converts glucose to energy and brings blood glucose levels back down. The rise and fall of blood sugar can influence hunger and satiety.

GLP-1 is short-lived in its natural form. Within one or two minutes the molecule gets dismantled by enzymes in the blood and cleared by the kidneys. So in the 1990s drug companies began creating synthetic versions of GLP-1, hoping to land on a durable, longer-lasting structure. Scientists found success in a compound in Gila monster saliva that is similar to human GLP-1 but much more stable. They attached a long chain of lipids that can bind to albumin—a protein in blood that serves as a carrier for the drug—and keep the compound active for hours or even days.

Around 2021 the story of GLP-1 receptor agonists took a dramatic turn. Demand for the drugs soared as celebrities and social media influencers began sharing their experiences using Ozempic off-label to achieve incredible weight loss. As more and more people took the drugs, stories spread about "food noise," and researchers started looking even more closely at what was going on in the brain.

Matthew Hayes, a nutritional neuroscientist at the University of Pennsylvania, who has studied GLP-1 and other gut hormones since 2006, explains that these drugs work partly because they slow digestion and modulate glucose levels. Some metabolic effect is causing weight loss, but it's "only contributing to a small degree," he says. “The way in which GLP-1 drugs are causing weight loss is without question due to suppression of food intake—to satiety,” Hayes adds. Increased satiety means people eat smaller, less frequent meals.

Scientists have known for some time that GLP-1 seems to have a secondary function as a satiety signal—a ping to the brain to stop eating. In 1996 researchers injected GLP-1 directly into the brains of hungry rats, and the rodents’ food intake decreased by as much as 95 percent. The study was some of the first evidence that the hormone had an effect in the brain. “All these feelings we have about being hungry or full are fundamentally brain-driven,” explains Herman Pontzer, an evolutionary anthropologist at Duke University and author of *Burn*, a book about the science of metabolism. “It makes sense that that’s where the mechanism of action is.” The brain was always involved, he says, but these new drugs are helping researchers zero in on the brain as a “center for regulating energy in and energy out.”

Appetite—the drive to eat—is biologically motivated by three core sensations: hunger, fullness and reward. “All three speak to each other, and for that, parts of the brain play a role,” explains Giles Yeo, a University of Cambridge professor who specializes in the genetics of body weight and the neuroscience of food intake. The hypothalamus—an almond-shaped structure near the base of the brain—is involved with feelings of hunger or starvation; the hindbrain, including regions of the brain stem, plays a role in fullness; and a distributed network fanning out from the midbrain to the prefrontal cortex orchestrates reward elements. It produces “the nice feeling you feel from eating chocolate that you don’t get from eating broccoli,” Yeo explains.

These brain regions all sense signals communicated via the gut-brain axis network—and scientists have found they are studded with GLP-1 receptors. “The receptor-expressing cells are everywhere, *everywhere*, throughout the brain,” Hayes says. “It’s almost a question of where are they *not*?" In fact, these receptors are now known to be abundant throughout the body. He thinks the reason so many cells and neurons are making GLP-1 receptors must be "because they want to respond to it."

When GLP-1 released from the gut latches on to the vagus nerve, the nerve sends signals up the brain stem to the nucleus tractus solitarius (NTS), a bundle of sensory neurons deep in the brain. The NTS is "the first place that [receives] all incoming satiety signaling from the gut," Hayes says. "It's like a processing hub for energy-balance control."

Because of its short lifespan, it's unlikely that natural GLP-1 produced in the intestines reaches high enough concentrations in the brain to affect satiety. But the NTS doesn't just relay incoming satiety signals from the gut—it also produces GLP-1 itself. Although the details of the mechanism are not yet fully understood, researchers have found that the primary source of GLP-1 in the brain is preproglucagon (PPG) neurons in the NTS. When activated, they act like an emergency brake at the end of the meal, flooding the brain with GLP-1 to send the message to stop eating. This effectively shuts down areas in the brain involved in feeding response, homeostatic controls, energy balance and decision-making about food—as well as the liking and wanting of food and impulsive behaviors associated with eating. For people with obesity, these neurons and hormonal activity might be a clue—one that the new drugs are bringing to light.

Compared with the naturally occurring hormone, the drugs have a stronger structure that better withstands degradation and allows them to be bioactive for hours—the newest formulas can last up to a week. This gives them the potential to act on the brain and stimulate those receptors for longer periods, Mojsov says.

There's growing evidence in animal models that the drugs make it through the blood-brain barrier—a protective membrane surrounding most of the organ— by penetrating “leaky” areas, such as the NTS. One way they get in is by riding on tanycytes, cells that aid in communicating energy balance between the peripheral and central nervous systems and enable nutrients, hormones and drugs to cross the blood-brain barrier.

“What’s interesting with these GLP-1-based drugs is that they’re lasting a lot longer than [natural] GLP-1,” Kanoski says. “This opens up a whole new pathway for communication.” Hayes says researchers are now looking into how much GLP-1 gets in, where exactly the drugs go, and what behaviors or functions they cause. “How deep into the brain do they get?” Hayes asks.

“My whole life was thinking about food,” says Meranda Hall, a 32-year-old administrator at a law firm in New York City. Hall was a cross-country runner in high school, and she kept exercising daily into adulthood. But she ate almost constantly and had been carrying extra weight since childhood. Even when Hall felt physically full, her brain was occupied by thoughts of food. “While I was eating,” she says, “I’d be thinking about the next meal.”

In August 2023, when Hall began taking Wegovy, she weighed 271 pounds. Nine months later she’d lost 78 pounds—as well as her intrusive thoughts about eating. The vanishing compulsion to overindulge didn’t stop with food, though. Hall says she used to be an enthusiastic social drinker, “an eight-margs-at-Taco-Tuesday type of girl.” Now she’s “a sober Sally.”

Like Hall, some people using GLP-1 receptor agonists report not only a decreased desire for food but reduced cravings for alcohol, nicotine, drugs, online shopping, nail picking—the list goes on. These effects are driving a spate of research into possible overlapping circuitry linking compulsive behaviors, appetite and satiety.

Neurons that produce dopamine—a chemical with pivotal involvement in motivation and pleasure—project to the nucleus accumbens, a midbrain structure important for experiencing reward, explains Patricia Sue Grigson, a neuroscientist and addiction researcher at Penn State College of Medicine. Like other brain structures, the nucleus accumbens has GLP-1 receptors. Studies have shown that in animals, dopamine release peaks after they eat a sweet meal of sucrose—and after they are exposed to cocaine or opioids. “But when there’s a GLP-1 agonist onboard, that’s pretty much squelched,” Grigson says. “You don’t get a peak to those rewards.”

In human experiments, scientists have observed that the same neurological pathways are stimulated when people gamble or take cocaine—or when their blood sugar levels have been artificially changed to stimulate fasting. Janice Jin Hwang, chief of the division of endocrinology and metabolism at the University of North Carolina at Chapel Hill, explains that “there are these networks of brain regions that have been very well characterized, mainly in addiction literature, that control our desire and motivation for food but also for addicting things.”

One reason food lights up reward pathways is that it’s essential for survival, says Lorenzo Leggio, an addiction researcher at the National Institute on Alcohol Abuse and Alcoholism and the National Institute on Drug Abuse. Visuals, taste, smell, memory, and other cues work together to reinforce food-seeking behavior, and “GLP-1 is trying to keep that process somehow under control,” Leggio says. “You start eating your cake. You love it, but what is preventing you from eating, like, 20 pieces of cake? GLP-1 is one of the triggers that is increasing your satiety,” he explains. “It’s reducing your reward, your pleasure, for that cake.”

Grigson and Leggio are among a growing number of researchers studying the effects of GLP-1 medications on this reward pathway for potential addiction treatments. In a recently completed clinical trial, Grigson tested the safety and efficacy of daily injections of a GLP-1 receptor agonist, liraglutide, in people receiving treatment for opioid use disorder. They saw an approximately 40 percent reduction in opioid cravings. (Results are not yet published.)

Grigson's team found that administering GLP-1 drugs in combination with buprenorphine, a current treatment for opioid use disorder, was also highly effective. Buprenorphine is an opioid itself, and people taking it as a medication may continue to experience drug cravings. Grigson hopes that adding GLP-1 medicines might help reduce the amount of buprenorphine needed. She is currently conducting a multisite follow-up study with researchers at New York University to investigate the treatment's effects on withdrawal. In May, Novo Nordisk announced that an upcoming clinical trial would investigate the drug as a treatment for liver disease—and explore its effects on alcohol consumption.

Endocrinologist Ania Jastreboff tells her patients that GLP-1 medications may change their desire to eat. But not everyone experiences the same dramatic effects. "I kind of preface by saying we don't know who will respond and how they will respond, how much weight a certain individual may lose, and how that may also impact their health overall," says Jastreboff, who is the director of Yale University's Obesity Research Center. Some people on semaglutide have lost as much as 20 percent of their body weight. But in one study, nearly 18 percent of users lost less than 5 percent. Some people are unable to tolerate the drugs because of their side effects, particularly severe nausea and diarrhea—a 2021 study showed 4.5 percent of people taking semaglutide discontinued the drug because of gastrointestinal issues. Scientists are now seeking to understand why the efficacy seems to vary so dramatically.

Natural GLP-1 levels may differ from person to person, and that could possibly explain varying susceptibility to weight gain or diabetes. Yeo studies why some people eat too much and says maybe it's because they "feel less full for every given mouthful of food they eat. And part of that could be because their GLP-1 levels don't go up as high for a given meal." In those people, Yeo says, synthetic GLP-1 drugs may work better than they would in people with naturally higher levels.

Hayes wonders whether people who aren't responsive to the drugs might have mutations in their GLP-1 receptors—and whether that could be part of why they gained excess weight in the first place. He speculates that GLP-1 receptors in some people may have genetic differences that might influence how well the hormone binds to the receptor and activates subsequent insulin and satiety pathways.

Pharmaceutical companies are now creating even more potent weight-loss medications by targeting multiple gut hormone receptors at once. Eli Lilly's tirzepatide uses synthetic versions of GLP-1 and gastric inhibitory polypeptide; clinical trials revealed it caused people to lose more than 25 percent of their body weight over 88 weeks.

The U.S. clinical trial registry shows that thousands of studies on GLP-1 receptor agonists are underway now. A large, multiyear study that showed semaglutide reduced risk of heart attack and stroke by 20 percent helped Wegovy gain FDA approval as a treatment for cardiovascular disease earlier this year. Weight reduction most likely played a large role in heart health, but researchers are also finding convincing early evidence that GLP-1—and the drugs—may reduce inflammation when bound to receptors. That observation is now opening up the drugs to clinical trials for diseases that seem less obviously related to metabolic disorders, including Alzheimer's, Parkinson's, depression and even cancer.

As new findings emerge, GLP-1 medications are changing how researchers and clinicians think about body weight. Health issues that manifest as diabetes or obesity have been primarily considered peripheral disorders—problems of the pancreas, liver or body tissue—Hwang says, but this is only part of the picture. Jastreboff, who has been working on obesity treatments for 15 years, says the drugs are probes to better understand the physiology of obesity. “They’ve enabled us to have a conversation about obesity as a complex neurometabolic disease,” she says.

For so long people who couldn’t lose weight and keep it off have been told that their willpower simply wasn’t strong enough, says Daniel Drucker, an endocrinologist at the University of Toronto, who researched GLP-1 alongside Mojsov in the 1990s. “We—including health-care professionals—would blame people challenged by their inability to lose weight,” he says. “It’s hard to think of diseases where we blame the individual. You would never say, ‘Your cancer came back; you didn’t really try hard enough.’” The study of GLP-1 could help erode the stigma associated with obesity and addiction by replacing assumptions with clear pathology.

“We all have the same reward systems that are absolutely essential to normal functioning,” Pontzer says, “and it’s only when we get toward the real far end of the spectrum on those reward responses that we get into trouble.” This hormonal system is evolutionarily ancient. “And we are now, in 2024, finding the advantages of the system through these drugs—we have hijacked it, if you will,” Hayes says. “We are at the precipice of the beginning.”

Lauren J. Young is an associate editor for health and medicine at *Scientific American*. She has edited and written stories that tackle a wide range of subjects, including the COVID pandemic, emerging diseases, evolutionary biology and health inequities. Young has nearly a decade of newsroom and science journalism experience. Before joining *Scientific American* in 2023, she was an associate editor at *Popular Science* and a digital producer at public radio’s *Science Friday*. She has appeared as a guest on radio shows, podcasts and stage events. Young has also spoken on panels for the Asian American Journalists Association, American Library Association, NOVA Science Studio and the New York Botanical Garden. Her work has appeared in *Scholastic MATH*, *School Library Journal*, *IEEE Spectrum*, Atlas Obscura and *Smithsonian Magazine*. Young studied biology at California Polytechnic State University, San Luis Obispo, before pursuing a master’s at New York University’s Science, Health & Environmental Reporting Program.

Mangrove Trees Are on the Move, Taking the Tropics with Them

As the climate warms, mangroves are migrating farther poleward, transforming the coast as they go

By Michael Adno

Mangroves along ocean shorelines prevent coastal erosion, sequester large amounts of carbon and provide valuable habitat for fish and birds, such as this anhinga, or “devil bird.”
Peter Essick

Two decades ago ecologist Ilka C. Feller heard about a plant advancing at an unprecedented rate into a coastal restoration site near Merritt Island on Florida’s Atlantic coast, midway between Miami and Georgia’s southern border. The plant was a mangrove, a tree that thrives in salt water and grows in stands along the ocean’s edge. The tree’s roots form a tangle that extends several feet out of the water, and its thin, tawny trunk and branches reach up into a dense canopy of waxy, jadelike leaves. Stands can stretch for miles, forming a biologically diverse forest that builds land by trapping sediment and protects coastlines from erosion, waves and storm surges. Mangroves have long defended coasts against hurricanes, cyclones and tsunamis, which researchers have shown are more deadly along shores without the tangled trees. Mangroves capture vast amounts of carbon, too.

There are more than 70 species of mangrove, adapted to hot habitats with soil low in oxygen. They filter out almost all the salt that enters their roots and thrive in places where few other plants can. They grow around the world but only at tropical and subtropical latitudes, in places that don’t have periodic freezes, which can prevent the plants from becoming established. Mangroves were not supposed to be at Merritt Island, but when Feller showed up in 2002 and started looking around, there they were.

Feller then drove to Tomoka State Park, about 70 miles farther north along the Atlantic coast. A park ranger told Feller there were no mangroves there, but she decided to look anyway. Sure enough, a few hundred yards past the ranger station she found small mangrove shrubs dotting the salt marsh. The following morning she drove another 40 miles north toward St. Augustine, Fla., which is only 60 miles south of the Georgia line, and she found a few isolated mangroves there, too.

Over the next 20 years Feller and her colleagues documented the poleward migration of mangroves in North America—and, by proxy, the shifting border of the subtropics. Since 1980 the world has lost more than 35 percent of its mangroves because of development, pollution and extreme weather. In parts of southern Florida, more than 50 percent have been destroyed. Yet in northern Florida, on the East Coast, mangroves have doubled in area. In Australia, the trees are migrating east to west rather than poleward. In Brazil, mangroves are creeping inland as rising seas push salt water deeper into the interior. And in South Africa, mangroves are migrating south, extending the subtropical boundary just as they are in Florida. It’s unclear how far the mangroves will travel. But the migration offers a picture of the future as temperatures climb, weather patterns shift and sea levels rise. And recent discoveries have reshaped almost everything scientists thought about their movements.

Feller began her career in 1975 as a scientific illustrator at the Smithsonian Institution. Her interest in mangroves began after she met a sponge curator who learned she was an experienced scuba diver. The curator asked Feller to develop an underwater drawing technique. Feller agreed, and soon she was depicting the coral reef off Belize on sheets of drafting film fastened to a plexiglass drawing board. She later joined that curator to research mangroves in Panama, where she swam up channels through remote mangrove forests with her drawing system. She drew the roots and the juvenile fish swimming among them, as well as seagrass and corals. When she wasn’t drawing, she collected insects. “I felt I could be there by myself all day and be totally happy,” Feller says. “It just turned out to be a place that I fit.”

For two decades Smithsonian ecologist Ilka C. Feller has been tracking mangroves' relentless migration northward from central Florida.
Peter Essick

Engrossed by the plants, Feller left Central America and went back to school for a Ph.D. in ecology. In 1997, just after turning 50, she returned to the Smithsonian as an ecologist. “I couldn't believe I got a job,” she says. In the past two decades Feller, now 77, has established research sites throughout the Caribbean, Belize, Panama, Ecuador, Australia and New Zealand, as well as Florida and the Gulf of Mexico's rim, studying the role of nutrients in mangrove stands, the species bound to the plants and the trees' migration. She is an author on more than 700 papers, including studies involving fieldwork in Saudi Arabia, Brazil and Indonesia, and she is widely regarded as a pioneer of experimental mangrove ecology. Some call Feller the godmother of mangrove ecology. Others call her “the mangrove queen.” (Her friends call her Candy.)

In the early 2000s Feller started recording mangroves she found north of St. Augustine, in the space between two different types of habitat, an ecosystem transition known as an ecotone. This region is where she could find clues to how the coastline would change as freezes became less frequent and hurricanes became more frequent. Storm currents can carry mangrove seeds far away, helping to broaden their range. But storms can harm the trees, too; in 2019 high winds, storm surge and prolonged floods from Hurricane Dorian destroyed more than half the mangrove forests of Grand Bahama.

More mangrove habitat could be a promising defense against sea-level rise. The trees also sequester more carbon than any other plant, both above and below the ground, another counter to climate change. But they could also overtake salt marshes, with consequences. The marshes—vast, open areas of green, grassy wetlands bisected by serpentine creeks, flooded daily by tides—line parts of coasts in the U.S. and many other countries. They support vegetation, host imperiled bird species and filter water, helping coastal ecosystems flourish. About 75 percent of U.S. salt marshes are in the Southeast, precisely where mangroves are appearing. Although mangroves build land faster than salt marshes do—in some cases, four times as fast—they’re much more vulnerable to cold temperatures. One severe freeze could eviscerate a forest, leaving the soft land vulnerable to erosion. “You could have that wetland go to water real quick,” says William “Ches” Vervaeke, an ecologist with the National Park Service.

In Florida, there are three species of mangrove: red, black and white. The red mangroves grow closest to the water, the black a bit farther in from the water’s edge, and the white in the higher elevations along the coast. Strangely, the three species are not related, but over millions of years they evolved in the same harsh environment. They resemble one another in form and location and in how they reproduce.

Mangroves are establishing forests along open salt marshes such as this one in Florida's Bulow Creek, 100 miles south of the Georgia line.
Peter Essick

By the time summer rains begin in Florida, red mangroves put out delicate chartreuse flowers, which will eventually bear fruit. Then a long, pen-shaped propagule with a lithe curve appears. If you pry open a mature propagule with your fingernail, you will find a seedling ready to fall out. The propagules drop off the plant—often into the water, where they may be carried a few inches or hundreds of miles. White mangroves produce tinier flowers, densely organized fruit and a propagule the size of a green bean. The black mangrove's propagule is slightly larger and asymmetrical.

As spring turned to summer in 2016, Feller's search took her up Florida's east coast until she finally headed into Nassau County, the state's northeasternmost county, where the Nassau River meets the sea. One afternoon she and a postdoctoral researcher were driving on a long, low bridge over the river toward Amelia Island, just shy of the Georgia line, when an emerald shrub in the distance caught their eye. They hit the brakes, parked and ran under the bridge toward the marsh. On the other side of a tidal creek, a black mangrove stood like a sentry. At 30.3 degrees north, the specimen was situated one third of the way between the equator and the North Pole, 60 miles north of its previously recorded range—by far the northernmost mangrove in the U.S. Later, they called it "Candy's Mangrove."

Soon after, Feller's peers started to find other black mangroves in that same area. Then, in 2021, Vervaeke was running a skiff along the Fort George River a few miles south of Amelia Island. Breaks of cedar trees line the bluffs along the river where dense stands of oaks are littered with resurrection ferns and orchids. The place "is kind of a hidden gem," he says. That day Vervaeke looked out from the small boat and spotted a set of bright green leaves amid the dull spartina grass. He realized he'd found a red mangrove, the northernmost in America, a companion to Candy's black mangrove. "I almost literally jumped out of the boat to go and look at that thing," he says.

Vervaeke expected to find black mangroves because they can tolerate lower temperatures to some extent, but a red mangrove was unprecedented. The species defied logic, proliferating on various banks of various rivers. "The intriguing part that captures my imagination," says ecologist Scott F. Jones, an assistant professor at the University of North Florida, "is that we still don't understand and therefore can't predict where exactly mangroves are going to show up."

Early one morning last December, Vervaeke led me through a tiny clump of cedar trees and sabal palms and into a marsh just north of Jacksonville, Fla., where the Fort George River meets the Atlantic in a plateau of sand banks flanking spartina grass and narrow channels. About 100 yards ahead of us Jones and Feller were examining leaves of mangrove shrubs. They were looking for signs of a type of crab and an insect, called a psyllid, that are typically found on trees farther south. As the trees creep north, so should the species tied to them.

A red mangrove, named for the color of its roots, stakes a claim on Fort George Island, only 20 miles from the Georgia border. Climate change is reducing freeze risk at increasingly higher latitudes.
Peter Essick

At one point, my head was buried inside a small shrub, following Feller's fingers as she aged the tree by counting sections of stem between nodes on its branches, which corresponded to seasons of growth (summer, long section; winter, short section.) Over time researchers noticed that active hurricane seasons were often followed by mild winters, which helped young plants take root after the storms spread propagules north.

Later that day Jones, Vervaeke, Feller and I headed north to the rim of Amelia Island to visit Candy's Mangrove. A light rain fell as we walked out toward the site. When we reached the ribbon of water separating the beach from the strand of marsh, it was too deep to cross without swimming. We opted for a warm lunch instead, waiting for the tide to drop. As we turned back toward the car, a bald eagle flew along a break of slash pines before landing in a nest. I wondered what the migration of this plant into the marsh would mean for birds and other animals, especially if mangroves replace salt marsh. The contrast between the two habitats is stark.

With more mangrove habitat, “there is a probable win for birds in many ways,” Andrew Farnsworth, a visiting scientist at the Cornell University Lab of Ornithology, later told me. Mangroves in southern Florida are essential habitat for migratory species, and more than 30 percent of Europe’s avian population spends winters in mangrove forests in West Africa. “Of course,” Farnsworth said, “this will be at the cost of some salt marsh specialists” such as eastern black rails, whimbrels and salt marsh sparrows.

Any real-world transformation probably wouldn’t be so simple. “I think these places are going to be a matrix of both salt marshes and mangroves,” says Samantha Chapman, a biology professor at Villanova University. But in some areas, she says, it might be a “total transition.” She thinks that, over time, there will be push and pull, creating additional habitat for some species while inevitably forcing others to look elsewhere. Many Florida game fish, for example, especially snook and tarpon, use mangrove estuaries as nurseries. In the past decade, however, researchers have found those juvenile snook and tarpon in marshes where there are no mangroves, including spots as far north as South Carolina. This shift shows that the fish can survive in varied habitats, and if other forces such as rising sea temperatures push them farther north, they may be able to adapt.

In other places, changes are more peculiar. Along the northern edge of the Amazon Delta, mangroves have been expanding inland as the rising sea inundates the low-lying coast. In some cases, that water follows navigational channels carved by residents and even the trails trod by wild water buffalo, forging paths along which salt water can creep inland and propagules can drift. The migration is “quite striking,” says Carlos David Santos, an ecologist and assistant professor at the NOVA School of Science and Technology in Portugal, who has been monitoring 500 miles of uninterrupted mangrove forest in Brazil. Some formerly freshwater lakes there are now composed entirely of salt water, displacing fish such as arapaima that are favored by local communities. What disturbs

Santos and others is how quickly changes are taking place: as habitat for shorebirds and macro invertebrates disappears along the coast, critical wetlands farther inland are rapidly becoming tight-knit mangrove forests.

Along the mouth of the Leichhardt River in Australia, increased precipitation and increased sediment accumulation have caused mangroves to expand out into the Gulf of Carpentaria; just a few miles west, mangroves are trending inland owing to prolonged periods of wetland flooding. In New Zealand, researchers have documented a rapid seaward migration of mangroves around Auckland. Over time people there altered rivers to suit agriculture, and increased sediment, coupled with higher levels of nitrogen and phosphorus from field runoff, has driven the mangroves' migration.

After tracking the movement of mangroves up Florida's coastline, Feller started to search through historical texts, looking for any clues about the trees' earlier whereabouts. That's when she found an anecdote that reshaped everything researchers knew about their range in the U.S.

In 1867 naturalist John Muir set out on foot for a journey across the South. His account of the trek was published posthumously in a 1916 book, *A Thousand-Mile Walk to the Gulf*. At one point, Muir crossed the St. Marys River from Georgia into Florida. As his boat drifted toward Fernandina Beach, a town on the river just south of the state line, he saw "clumps of mangrove and forests of moss-dressed, strange trees appearing low in the distance." This would have been roughly 15 miles north of Candy's Mangrove. If the description was accurate, the current consensus that mangroves had never grown so far north was wrong. Feller eventually found another mention from 1837 and a record from 1821. She ended up tracing the trail back to 1788, when French botanist and explorer André Michaux found mangroves south of Candy's.

Researchers Ches Vervaeke (*left*) and Scott Jones (*right*) document a black mangrove beside the St. Marys River, which forms part of the border between Florida and Georgia.
Peter Essick

Feller then sketched a time line of freezes based on citrus growers' records, along with a map of hurricane paths. (After Hurricane Irma in 2017, Feller found mangrove propagules along the beach on Jekyll Island, 20 miles north of the Georgia line. She even found intact roots and branches.) She sent all these notes to Kyle Cavanaugh, an assistant professor at the University of California, Los Angeles, Institute of the Environment and Sustainability. Cavanaugh collected climate data for the Florida coast from 1950 to 2017. And Wilfrid Rodriguez, a researcher at the Smithsonian, pulled together aerial images of the Matanzas Inlet just south of St. Augustine going back to 1942. Together the records, data and imagery revealed a curious expansion and contraction of mangroves.

The team concluded, in a 2019 paper, that mangroves were not simply migrating north. Instead there was sophisticated, long-term movement of plants both northward and southward—"regime shifts" dictated by weather. Freezes pushed the mangrove boundary south. Often the habitat was replaced by salt marsh. But during mild winters and active hurricane seasons, mangrove forests slowly migrated north again.

In northeastern Florida, fluid transformations between mangroves and salt marsh occurred at least six times between the late 1700s and 2017, Feller says. But the researchers say that with annual temperatures rising relentlessly, freezes decreasing and hurricanes becoming more powerful, the northward migration of mangroves in recent years may become permanent. Soon enough, mangroves will spill into Georgia and then inevitably into South Carolina. The trees aren't simply marching north; they are taking leaps when the elements allow and falling back only slightly, if at all, when cool air reaches south.

In January 2024 Vervaeke and Jones invited me to join them as they looked for the next biological borderland of the subtropics. They dropped a skiff into the Nassau River, a few miles north of Candy's Mangrove, and headed north as the tide rose, carving through the backcountry until we reached the Intracoastal Waterway, which runs north to south. The first stretch of our search didn't yield anything. Four miles farther north, though, we all shouted, "There!" The unmistakable hue of a red mangrove sat beside a stand of cedar trees. Vervaeke and Jones were ecstatic; this was farther north than any other mangrove they had seen, and it was a red, too. Minutes later we found yet another red mangrove—the new northernmost tree. Using a GPS device, a computer tablet and an orange notebook, Vervaeke and Jones recorded the coordinates, elevation and plant measurements.*

As mangroves push poleward, they could transform salt marshes into a matrix of trees and grasses—or take over completely.
Peter Essick

We continued north toward Fernandina Beach. Less than five minutes later, Jones pointed: “There.” Another mangrove, this time a black one. The day continued like that as we found tree after tree farther and farther north—in the Amelia River, along Lanceford Creek and deep in the network of marshes that make up Tiger Island near Georgia’s southern border. By the time we reached the state line, where the St. Marys River runs into the Atlantic, we had recorded 19 successive “northernmost” mangroves, most of which were red.

With the wind dropping, Vervaeke couldn’t resist making an unplanned run across the river into Georgia. The marsh there feels endless, the live oaks along the shoreline ancient. The vast span of the St. Marys River pours out toward Cumberland Island, between the lime-green edges of the marsh. As we pressed against another shoreline, one plant poked up above the grass. Jones was skeptical, but Vervaeke smiled. Could it really be a mangrove, the first in Georgia? As Vervaeke set the boat onto an oyster bar, Jones ran over toward the plant. He reached the top of the bank and looked back, beaming. Vervaeke just laughed and gathered his equipment. “I’ll be damned,” he said.

On the run home, Vervaeke, who had tattooed the prior northernmost mangrove's coordinates on his arm, thought about making an appointment to update it. Back in the truck, they called Feller to tell her they'd found 21 new northernmost mangroves. Two of them were in Georgia. "No way!" the mangrove queen shouted. "I'll be there soon."

**Editor's Note (10/2/24): This sentence was edited after posting to correct the description of the GPS device.*

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Can AI Save Schrödinger’s Cat?

Outcomes in quantum mechanics depend on observations. But must the observer be human?

By Anil Ananthaswamy

MondoWorks

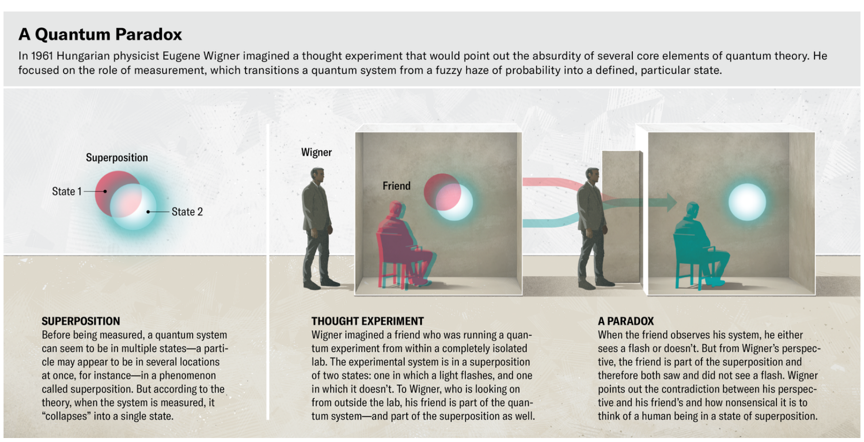
One of the most confounding concepts to emerge from the cauldron of early 20th-century physics was the idea that quantum objects can exist in multiple states simultaneously. A particle could be in many places at once, for example. The math and experimental results were unequivocal about it. And it seemed that the only way for a particle to go from such a “superposition” of states to a single state was for someone or something to observe it, causing the superposition to “collapse.” This bizarre situation raised profound questions about what constitutes an observation or even an observer. Does an observer merely discover the outcome of a collapse or cause it? Is there even an actual collapse? Can an observer be a single photon, or does it have to be a conscious human being?

This last question was highlighted in 1961 by Hungarian physicist Eugene Wigner, who came up with a thought experiment involving himself and an imaginary friend. The friend is inside a fully isolated laboratory, making observations of a quantum system that's in a superposition of two states: say, one that causes a flash of light and one that doesn't. Wigner is outside, observing the entire lab. If there's no interaction between the lab and the external world, the whole lab evolves according to the rules of quantum physics, and the experiment presents a contradiction between Wigner's observations and those of his friend. The friend presumably perceives an actual result (flash or no flash), but Wigner must regard the friend and the lab as being in a superposition of states: one where a flash is produced and the friend sees it, and one where there is no flash and the friend does not see anything. (The friend's state is not unlike that of Schrödinger's cat while it is dead and alive at the same time.)

Eventually Wigner asks the friend what he saw, and the entire system supposedly collapses into one or the other state. Until then, the "friend was in a state of suspended animation before he answered," Wigner wrote, pointing out the absurdity. A paradox was born.

Over the past decade physicists have proposed and performed limited versions of the experiment. Of course, they can't carry it out as Wigner envisioned, because human beings can't be put in superposition. But scientists have tested the idea by using photons—particles of light—in place of Wigner's friend. In a basic sense, an "observation" is the interaction of the environment, or some outside system, with the system being observed. One simple observation is for a single photon to interact with the system. This interaction then puts the photon into a superposition of states, so that it carries information about the system it observed. These experiments proved that Wigner's paradox is real, and to resolve it, physicists may have to give up some of their dearly held beliefs about objective reality. But single photons obviously fall short of human observers.

To understand the full implications of Wigner's idea, scientists have dreamed up an observer that comes much closer to the original friend, albeit one that borders on science fiction. Howard M. Wiseman, director of the Center for Quantum Dynamics at Griffith University in Brisbane, Australia, and his colleagues imagine a futuristic "friend" that's an artificial intelligence capable of humanlike thoughts. The AI would be built inside a quantum computer. Because the computations that give rise to such an AI's thoughts would be quantum-mechanical, the AI would be in a superposition of having different thoughts at once (say, "I saw a flash" and "I did not see a flash"). Such an AI doesn't exist yet, but scientists think it's plausible. Even if they can't carry out the experiment until the distant future, just thinking about this type of observer clarifies which elements of objective reality are at stake, and may have to be abandoned, in resolving Wigner's paradox.



Renato Renner, head of the research group for quantum information theory at ETH Zurich and someone who has also worked on the Wigner's-friend paradox, is enthusiastic about this use of a quantum-mechanical AI. "Obviously, we cannot do a Wigner's-friend experiment with real humans," he says. "Whereas if you go to the other extreme and just do experiments with single [photons], that's just not so convincing. [Wiseman and his team] tried to find this middle ground. And I think they did a very good job."

Of course, it's possible that an AI's thoughts could never stand in for observations made by a human, in which case Wigner's paradox will continue to haunt us. But if we agree that such an AI could be built, then detailing how such an experiment could be run helps to reveal something fundamental about the universe. It clarifies how we can determine who or what really counts as an observer and whether an observation collapses a superposition. It might even suggest that outcomes of measurements are relative to individual observers—and that there's no absolute fact of the matter about the world we live in.

The proposed Wigner's AI-friend experiment is a way of testing a so-called no-go theorem about some fundamental tenets of reality that may or may not be true. The proposal was devised by Wiseman, his Griffith University colleague Eric Cavalcanti and Eleanor Rieffel, who heads the Quantum Artificial Intelligence Laboratory at the NASA Ames Research Center in California. The theorem starts with a set of assumptions about physical reality, all of which seem extremely plausible.

The first: we have the freedom to choose the settings on our measuring devices. The second: all physics is local, meaning an intervention in one part of spacetime cannot influence something in another part of spacetime any faster than the speed of light. The third: observed events are absolute such that the outcome of a measurement is real for all human observers even if it may not be knowable to all. In other words, if you toss a quantum coin and get one of two possible outcomes, say heads, then that fact holds for all observers; the same coin can't appear to land on tails for some other observer.

With these assumptions in place, the researchers took on Wigner's view of human consciousness. Wigner, in his musings, argued that consciousness must be dealt with differently than all else. To drive home this point in his thought experiment, he asks us to consider an atom as the "friend" inside the lab. When the atom interacts with, or measures, the particle, the entire system ends up in a superposition of the particle flashing and the atom absorbing this light and entering a higher energy state, and the particle not flashing and the atom remaining in its ground state. Only when Wigner examines the lab does the atom enter one or the other state.

This isn't at all hard to accept. An atom can indeed remain in a superposition of states as long as it's isolated. But if the friend is a human being, then Wigner's perspective from outside the lab and the friend's perspective from within the lab are at odds. Surely, the friend knows whether a flash has occurred even if Wigner has not perceived it yet. "It follows that the being with a consciousness must have a different role in quantum mechanics than the inanimate measuring device," Wigner wrote. But does his argument make sense? Is a human observer fundamentally different than, say, an atom acting as an observer?

Wiseman, Cavalcanti and Rieffel tackled this question head-on by adding a fourth assumption, which they call the friendliness assumption. It stipulates that if an artificial intelligence displays human-level abilities, its thoughts are as real as those of a human. The friendliness assumption is explicit about what constitutes an observer: "it's a system that would be as intelligent as we are," Cavalcanti says.

The team settled on the notion of “intelligence” rather than “consciousness” after much debate. During their discussions Cavalcanti argued that intelligence is something that can be quantified. “There’s no possible test to determine whether or not anyone else is conscious, even a human being, let alone a computer,” he says. Therefore, if a human-level AI were built, it would be unclear whether it was conscious and it would also be possible to deny that it was. “But [it would be] much harder to deny that it’s intelligent,” Cavalcanti says.

After describing all these assumptions in detail, the researchers proved that their version of Wigner’s-friend experiment, were it to be done to a high accuracy using an AI based inside a quantum computer, would result in a contradiction. Their no-go theorem would then imply that at least one of the assumptions must be wrong. Physicists would have to give up one of their cherished notions of reality.

The no-go theorem can be tested only if scientists someday invent an AI that’s not just intelligent but capable of being put in a superposition—a requirement that necessitates a quantum computer. Unlike a classical computer, a quantum computer uses quantum bits, or qubits, which can exist in a superposition of two values. In classical computation, a circuit of logic gates turns some input bits into output bits, and the output is definitive. In quantum computers, the output can end up in a superposition of states, each state representing one possible result. It’s only when you query the quantum computer that the superposition of possible results is destroyed (according to traditional interpretations of quantum mechanics), producing a single output.

For their theorem, Wiseman, Cavalcanti and Rieffel assume that a powerful AI capable of human-level intelligence (a descendant of today’s ChatGPT, for example) can be implemented inside a quantum computer. They call this machine QUALL-E, after OpenAI’s image-generating AI DALL-E and Pixar’s robot WALL-

E. The name also nods to the word “quale,” which refers to the quality of, say, the color red as perceived by a person. The team tried to figure out how feasible it is to develop an actual QUALL-E. This was Rieffel’s area of expertise.

Turning a futuristic classical AI algorithm into one that can work inside a quantum computer involves multiple steps. The first, Rieffel says, is to use well-established techniques to make the classical computation reversible. A reversible computation is one where the input bits in a logic circuit produce some output bits, and those output bits, when fed to the reversed logic circuit, reproduce the initial input bits. “Once you have a reversible classical algorithm, you can just immediately translate it to a quantum algorithm,” she says. If the classical algorithm is complex to start with, making it reversible adds considerable computing overhead. Still, you get an estimate of the required overall computing power. This stage reveals the approximate number of logical qubits necessary for the computation.

Another source of computing overhead is quantum-error correction. Qubits are fragile, and their superpositions can be destroyed by myriad elements in the environment, leading to errors in computation. Hence, quantum computers need additional qubits to keep track of accumulating errors and provide the necessary redundancy to get the computation back on track. In general, you need 1,000 physical qubits to do the work of one logical qubit. “That’s a big overhead,” Rieffel says.

Her initial estimates of the computation power needed for a quantum-mechanical, human-level AI, using the current capabilities of fault-tolerant quantum gates, were staggering: for thoughts that would take a human one second to think, QUALL-E would require more than 500 years. It’s clear that QUALL-E isn’t going to be built anytime soon. “It’s going to be decades and require a lot of innovations before something like this proposed experiment could be run,” Rieffel says.

But Rieffel and her collaborators are optimistic. Wiseman takes inspiration from how far classical gates have come in the 150 years since Charles Babbage invented his analytical engine, considered by many to be the first computer. “If quantum computers had the same type of trajectory for that length of time, [then] at some point in the future, I think, this is plausible,” Wiseman says. “In principle, I can’t see any reason that it can’t be done, but it is significantly harder than I had initially thought.”

Renner is also optimistic about the proposal. “It’s at least something we can technologically, in principle, achieve, in contrast to having real humans in superposition,” he says. Rieffel thinks smaller but still complex versions of QUALL-E that don’t necessarily display human-level intelligence could be built first. “It may be enough to do a nematode or something like that,” she says. “There are a lot of exciting possibilities between a single photon and the experiment we laid out.”

Let’s assume for now that one day QUALL-E will be built. When that happens, QUALL-E will play the role of Charlie, who sits between two human observers called Alice and Bob, in a Wigner’s-friend-type experiment. Charlie and his lab are quantum-mechanically isolated. All three entities must be far enough away from one another that no one’s choice of measurement can influence the outcomes of measurements made by the other two.

The experiment begins with a source of qubits. In this scenario, a qubit can be in some superposition of the values +1 and –1. Measuring a qubit involves specifying something called a basis—think of it as a direction. Using different measurement bases can yield different results. For example, measuring thousands of similarly prepared qubits in the “vertical” direction might produce equal numbers of +1 and –1 results. But with measurements in a basis that is at some angle to the vertical, you might observe +1 more often than –1, for example.

> What constitutes an observer? Can an observer be a single photon, or does it have to be a conscious human being?

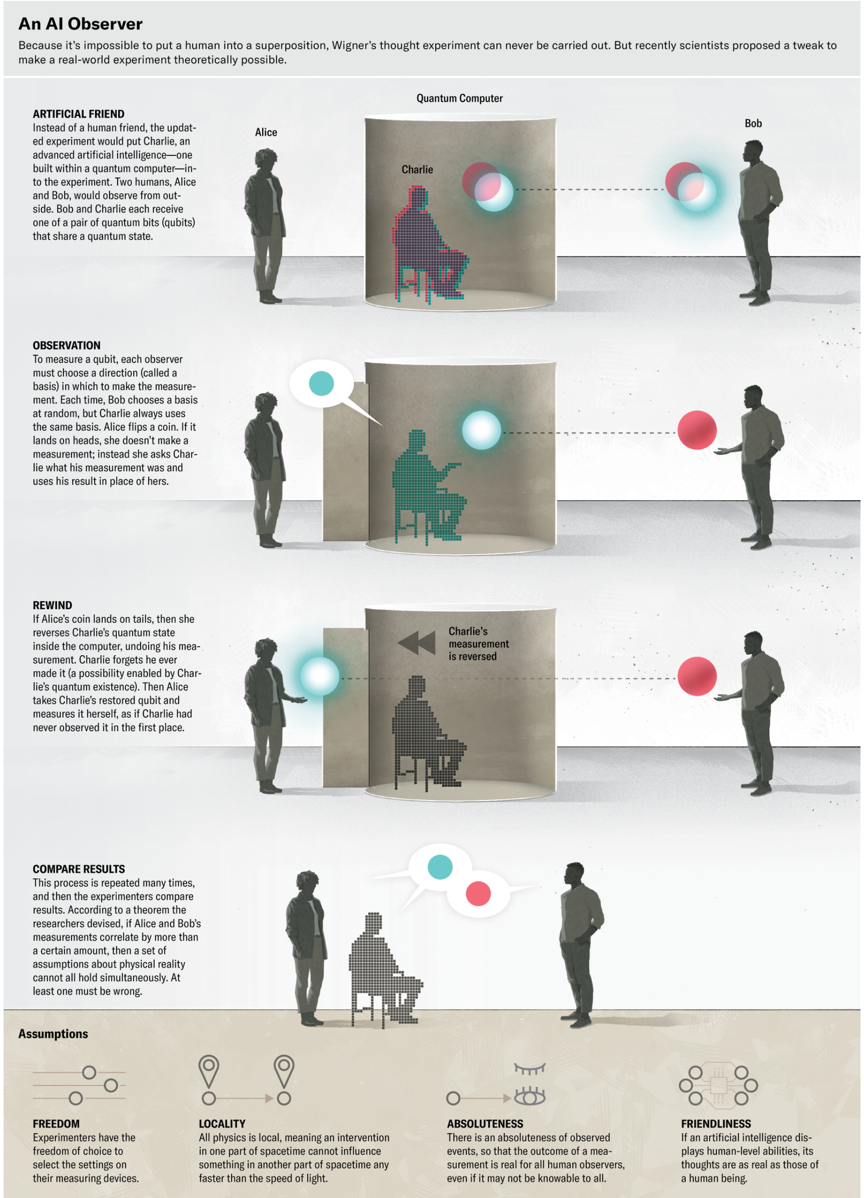
The experimenter begins by taking two qubits that are described by a single quantum state—such that measurements of the quantum state of each qubit in the same basis are always perfectly correlated—and sends one each to Bob and Charlie. Bob measures his qubit by choosing one of two bases at random. Charlie, however, always measures the qubit with the same basis. Meanwhile Alice flips a coin. If it comes up heads, she doesn't make a measurement; instead she asks Charlie for the outcome of his measurement and uses that as if it were the result of her own measurement.

But if the coin comes up tails, Alice reverses everything that Charlie did in his lab. She can do this because Charlie is a fully isolated quantum system whose computation is reversible. This rewind includes wiping Charlie's memory of having ever taken a measurement—an action that would be impossible with a human observer. But undoing the observation and the observer's recollection of it is the only way to take the system back to its initial conditions and thereby retrieve Charlie's qubit in its original, unmeasured state.

An important condition is that there is no communication between Charlie and Alice if she flips tails. The researchers emphasize that because Charlie is an AI agent capable of human-level thoughts, the experiment can be done only if "Charlie agreed to be in it," Wiseman says. "He knows that he's going to do something and then potentially that's going to be undone." Reversing the measurement and recovering the original qubit are crucial for Alice's next step: she then observes Charlie's qubit in a different basis than the one Charlie used.

Alice, Charlie and Bob carry out this entire process many times. The end result is that Bob's measurements always represent his own observations, but Alice's results are sometimes her own measurements (if she flips tails) and sometimes Charlie’s (if she flips heads). Therefore, her accumulated results represent a random mix of measurements taken by an outside observer and measurements made by an observer within the quantum superposition. This mix allows scientists to test whether the two kinds of observers see different things. At the end of the trials, Alice and Bob compare their results. Wiseman, Cavalcanti and Rieffel derived an equation to calculate the amount of correlation between Alice and Bob’s outcomes—essentially, a measurement of how often they agree.

Calculating the amount of correlation is difficult; it involves determining what value of the outcome you might expect for each measurement basis, based on the entire set of measurements, and then plugging those values into an equation. At the end of the process, the equation will spit out a number. If the number exceeds a certain threshold, the experiment will violate an inequality, suggesting a problem. Specifically, a violation of the inequality means the set of assumptions about physical reality the researchers built into their theorem cannot all hold simultaneously. At least one of them must be wrong.



Matthew Twombly

Because of the way the scientists set up their no-go theorem, this outcome is what most physicists expect. “I’m confident that such an experiment, if performed, would violate the inequalities,” says Jeffery Bub, a philosopher of physics and a professor emeritus at the University of Maryland, College Park.

If so, physicists would have to dump their least favorite assumption about physical reality. It wouldn’t be easy—all the assumptions are popular. The idea that physicists are free to choose their measurement settings, the notion of a universe that is local and obeys Albert Einstein’s laws, and the expectation that the outcome of a measurement one makes is true for all observers all seem sacrosanct on their face. “I think most physicists, if they were made to think about it, would want to hold on to all these assumptions,” Wiseman says. More physicists might be ready to doubt the friendliness assumption, though—the idea that “machine intelligence can entail genuine thoughts,” Wiseman says.

But if machines can have thoughts and the inequality is violated, then something must give. Adherents of different quantum theories or interpretations will point fingers at different assumptions as the source of the violation. Take Bohmian mechanics, developed by physicist David Bohm. This theory argues that there is a hidden, nonlocal reality behind our everyday experience of the world, allowing events here to instantaneously influence events elsewhere, regardless of the distance between them. Proponents of this idea would ditch the assumption of a local reality that obeys Einstein’s laws. In this new scenario, everything in the universe influences everything else, simultaneously, however weak the effect. The universe already has a small amount of nonlocality baked into it from quantum mechanics, although this quality still hews to Einstein’s view of a local universe. Given that this tiny amount of nonlocality is what allows for quantum communications and quantum cryptography, it’s nearly impossible to imagine the fallout of a profoundly nonlocal universe.

Then there are so-called objective collapse models of quantum physics, which argue that superpositions of states collapse randomly on their own, and measurement devices simply discover the outcome. Collapse theorists “would give up the idea that the quantum computer could simulate a human, or the friendliness assumption,” Renner says. They would believe a quantum computer, given enough qubits to completely compensate for any errors that arise in the computation, should protect the superposition indefinitely—it should never collapse. And if there’s no collapse, there’s nothing to observe.

Other physicists likely to give up on the friendliness assumption are those who adhere to the standard Copenhagen interpretation of quantum mechanics. This view argues that any measurement requires a hypothetical "Heisenberg cut"—a notional separator that divides the quantum system from the classical apparatus making measurements of it. Adherents of this interpretation "would deny the assumption that a universal quantum computer would ever be a valid agent because that computer remains in a superposition and therefore is on the quantum side of the Heisenberg cut," Renner says. "It's just on the wrong side to be an observer." Such physicists would argue that the thoughts of an AI built inside a quantum computer are not a proxy for human thoughts. Bub is partial to this view. "I would reject the friendliness assumption in the context of such an experiment," he says.

There's a more striking alternative: give up the assumption about the absoluteness of observed events. Letting go of this one implies that observations of the same event lead to different outcomes depending on who's doing the measuring (whether that observer is a conscious human, an AI or a photon). It's a position that sits well with many-world theorists (those who follow a theory formulated by physicist Hugh Everett), who think superpositions never get truly destroyed—that when a measurement is made, each possible state branches off to manifest in a different world. They would question the absoluteness of observed events because in their theory, thoughts or observations are absolute in their respective worlds, not in all worlds.

Some interpretations of quantum physics argue that even if there's only one world, the outcomes of measurements may still be relative to an observer rather than an objective fact for everyone. Renner, for one, is open to the idea that the result of a quantum coin toss might be simultaneously tails for one observer and heads for another. "We probably have to give up the absoluteness of observed events," he says, "which I think really has very little justification in physics." He points to Einstein's theories of relativity as examples.

When you measure the velocity of an object, it’s relative to your frame of reference. Someone with another frame of reference would have to perform a well-defined mathematical translation, given by the rules of relativity, to determine the same object’s velocity from their own point of view.

No such rules exist, however, to translate things in the quantum world from one observer’s point of view to another’s. “We have almost no clue what this rule should be at the moment,” Renner says. Scientists have largely avoided thinking about the observer until recently, he adds. “Only now are people starting to even ask that question, so it’s not surprising that it doesn’t yet have an answer.” As reasonable as this notion may sound to some physicists, it’s a pretty radical change from how most people see the world. If measurement outcomes are relative to observers, that calls into question the entire scientific enterprise, which depends on the objectivity of experimental findings. Physicists would have to figure out a way to translate between quantum reference frames, in addition to classical reference frames.

An even more striking result of the experiment would be if the inequality weren’t violated. Wiseman thinks that although there’s a very small chance of this happening, we can’t be sure it won’t. “By far, the most interesting thing would be if we tried to do this experiment and just can’t get a violation,” he says. “That’s huge.” It would mean the laws of physics are different from what physicists think they are—an outcome that’s an even bigger shake-up than giving up one of the assumptions in the theorem.

No matter what, if this Wigner’s-friend experiment ever comes to be, its implications will be a big deal. That’s why scientists are so interested in the idea, even though the AI and computing technology needed to carry it out are a ways off. “It hasn’t altered the fact that I still think of this as a serious proposal—not [just] pie in the sky,” Wiseman says. It’s “something that I really hope, even after I’m dead, experimenters are going to be motivated to try to achieve.”

If scientists generations hence pull off this feat, they will probably grasp something about the nature of quantum reality that has so far eluded the best of minds. It just might be that the status of experimental observations goes the way of much else in physics—from a vaunted position to nothing special. The Copernican revolution told us Earth is not the center of the solar system. Cosmologists now know that our galaxy is in no more distinctive a location than that of the 100 billion other galaxies out there. In much the same way, observed events could turn out to have no objective status. Everything could be relative down to the smallest scales.

Anil Ananthaswamy is author of *The Edge of Physics* (Houghton Mifflin Harcourt, 2010), *The Man Who Wasn't There* (Dutton, 2015), *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality* (Dutton, 2018), and *Why Machines Learn: The Elegant Math Behind AI* (Dutton, 2024).

How the Math of Cracks Can Make Planes, Bridges and Dams Safer

Better predictions of how cracks grow can make machines and structures more reliable

By Manil Suri

Wayne Brezinka

At 11:03 A.M. on April 17, 2018, metal fatigue caused a fan blade to break off inside the left engine of Southwest flight 1380 en route from New York to Dallas at 32,000 feet. The rupture blew the exterior of the engine apart, bombarding the fuselage with metal fragments and shattering a window in row 14. In the rapid cabin decompression that followed, a passenger was sucked halfway out the damaged window and sustained fatal injuries. The pilots were able to prevent a larger tragedy by landing the plane safely in Philadelphia.

The number of airplane accidents caused by metal fatigue has been steadily increasing for years, rising to a high of 30 during the 2010s, the decade most recently tabulated. Several of these incidents were serious enough to require emergency landings. Although it seems like the Boeing 737 Max 9 door plug that popped out at 16,000 feet in January 2024 was probably missing bolts, the Max family of planes had experienced a fatigue-related safety issue in 2019, when wing slats susceptible to cracks had to be replaced.

Airplanes have been described as “two million parts flying in close formation,” and a lot can go wrong with them. Successive flights subject these parts to cycles of intense stress and relaxation, during which small defects, unavoidable in the manufacturing process, can lead to tiny cracks. Once a crack grows long enough, as one did at the base of Southwest 1380’s fan blade, adjacent components can break off. Aircraft designers therefore need to predict the maximum stress that components will have to endure.

Cracks can show up in structures as huge as dams, bridges and buildings and as biologically intimate as the bones and teeth in our own bodies. Engineers at the National Institute of Standards and Technology are modeling the 2021 collapse of a beachfront condominium in Florida, for instance, to understand what role cracks in the supports might have played in the disaster. And a recent analysis of the *Titan* submersible that imploded in the North

Atlantic Ocean has identified areas that might have fractured. In metal and concrete and tooth enamel, cracks form in areas that are subjected to the most intense stresses—and they can be most dangerous when they exceed a critical length, which depends on the material.

Engineers can use similar tools to study an enormous variety of cracks and to prevent failures. As an important defense against failures, a machine or structure should be subjected to physical tests, but such testing can be expensive and may not always be feasible. Once a part is being used, it should be periodically inspected, which is also expensive.

Beyond these hands-on strategies, there is a crucial third aspect of preventing failure: computer simulation. During development, simulations help engineers create and test designs that should remain viable under many different conditions and can be optimized for factors such as strength and weight. Airplanes, for instance, need to be as light and durable as possible. Done properly, simulations can help prevent mishaps.

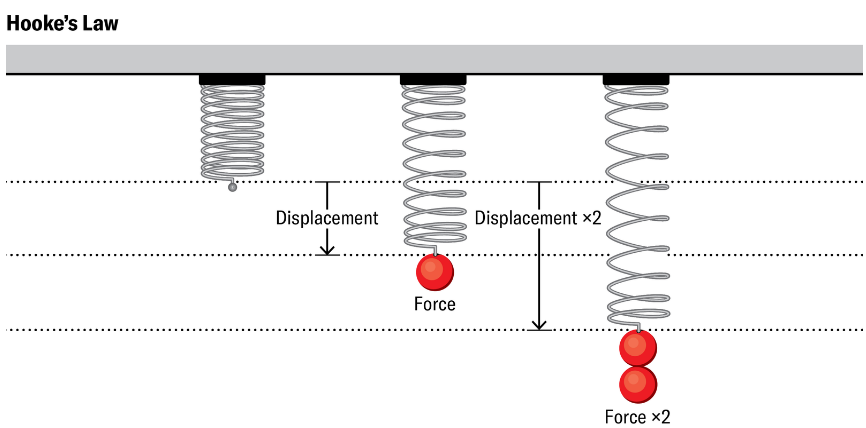
> As the U.S. embarks on a massive program to overhaul its infrastructure, improving the reliability of computer simulations can help ensure safety.

The soundness of these simulations is essential for safety—but they don't get the same scrutiny or regulatory oversight as manufacturing defects, maintenance errors or inspection frequency. Engineers analyzing the 1991 collapse of a Norwegian oil platform found that because of a simulation error, one of the internal supporting walls was predicted to experience only about half as much stress as it actually did. Consequently, it was designed with much lighter reinforcement than needed, and it failed.

As the U.S. embarks on a massive program to overhaul its infrastructure, ensuring safety and durability will be critical.

Robust computer simulations can help with both while reducing the need for expensive physical testing. Concerningly, however, the simulations that engineers use are often not as reliable as they need to be. Mathematics is showing how to improve them in ways that could make cars, aircraft, buildings, bridges, and other objects and structures safer as well as less expensive.

Given the complexity of 21st-century machines, it’s curious that an anagram published in the 1670s underpins their mechanics. Known as Hooke’s law, *ut tensio, sic vis* (“as the extension, so the force”) states that the deformation of an elastic object, such as a metal spring, is proportional to the force applied to it. The law remains in effect only if the object stays elastic—that is, if it returns to its original shape when the force is removed. Hooke’s law ceases to hold when the force becomes too large.



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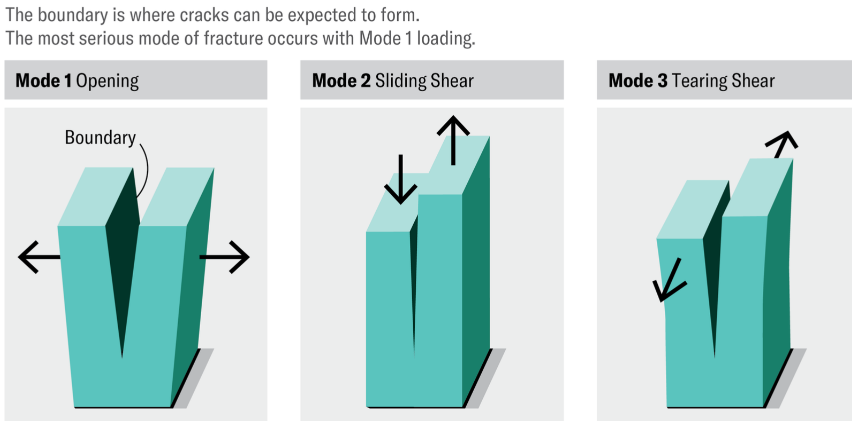
In higher dimensions, the situation gets more complicated. Imagine pressing down lightly on a cube of rubber glued to a table. In this case, the reduction of the cube’s height compared with its original height, the “strain,” is proportional to the force you apply per unit area of the cube’s top surface, the “stress.” One can also apply varying forces to the different faces at different angles—subject the cube to diverse “loadings,” as engineers say. Both the stress and the strain will then have multiple components and typically vary from point to point. A generalized form of Hooke’s law will still hold, provided the loading is not too large. It says that the stresses and strains remain proportional, albeit in a more complicated way. Doubling all the stresses will still double all the strains, for example.

People use Hooke's law to analyze an astonishing variety of materials—metal, concrete, rubber, even bone. (The range of forces for which the law applies varies depending on the material's elasticity.) But this law provides only one of many pieces of information needed to figure out how an object will respond to realistic loadings. Engineers also have to account for the balance of all the forces acting on the object, both internal and external, and specify how the strains are related to deformations in different directions. The equations one finally gets are called partial differential equations (PDEs), which involve the rates at which quantities such as stresses and strains change in different directions. They are far too complicated to be solved by hand or even to be solved exactly, particularly for the complex geometries encountered in, for instance, fan blades and bridge supports.

Even so, beginning with, most notably, Vladimir Kondrat'ev in 1967, mathematicians have analyzed these PDEs for common geometries such as polygons and polyhedrons to gain valuable insights. For instance, stresses will usually be highest in the vicinity of any corners and edges. That is why it's easier to tear a sheet of foil if you first make a nick and then pull the foil apart starting from the point of the cut.

The problem is that many machine parts whose integrity is essential for safety incorporate such features in their design. Although corner tips and edges are generally rounded as much as possible, cracks are still more likely to form in these places. Loadings that pull the sides of a boundary directly apart are the most likely to expand a crack. So engineers must pay special attention to these locations and the forces acting around them to ensure that the maximum stresses the object can endure before it starts breaking apart are not exceeded.



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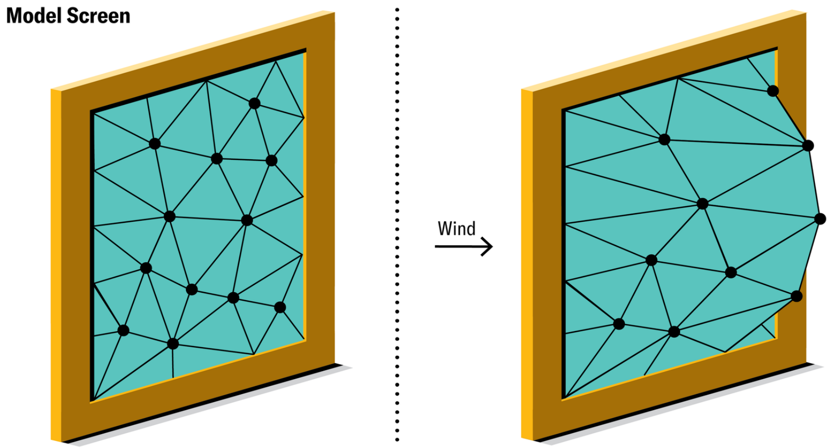
To do so, they need to find approximate solutions to the object's PDEs under a variety of realistic loadings. Engineers have a handy technique for this purpose, called the finite element (FE) method. In a landmark 1956 paper, engineers M. Jonathan Turner, Ray W. Clough, Harold O. Martin and L. J. Topp point out that to understand how an object deforms, it helps to think of it as being made of a number of connected parts, nowadays referred to as finite elements.

Let's say you want to find out how a two-dimensional elastic object, such as a tautly stretched screen fixed along its perimeter, deforms when subjected to a powerful wind hitting it perpendicularly. Imagine the screen being replaced by a bunch of linked triangular facets, each of which can move and stretch but must remain a flat triangle. (One can also use a quadrilateral.) This model screen made of triangles is not the same as the original, smooth screen, but it provides a more tractable problem. Whereas for the actual screen you would need to find the displacement at each point—an infinite problem—for the model screen made of triangles you need to find only the final positions of each triangle corner. That's a finite problem, relatively easy to solve, and all the other positions of the screen surface can be deduced from its solution.



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A governing principle from physics states that the screen will assume the shape for which the potential energy, which it possesses by virtue of its position or configuration, is a minimum. The same principle predicts that after a guitar string is plucked, it will eventually return to a straight-line shape. This principle holds for our simplified FE screen as well, yielding a set of relatively simple “linear” equations for the unknown displacements at the nodes. Computers are very adept at solving such equations and can tell us how the model screen deforms.

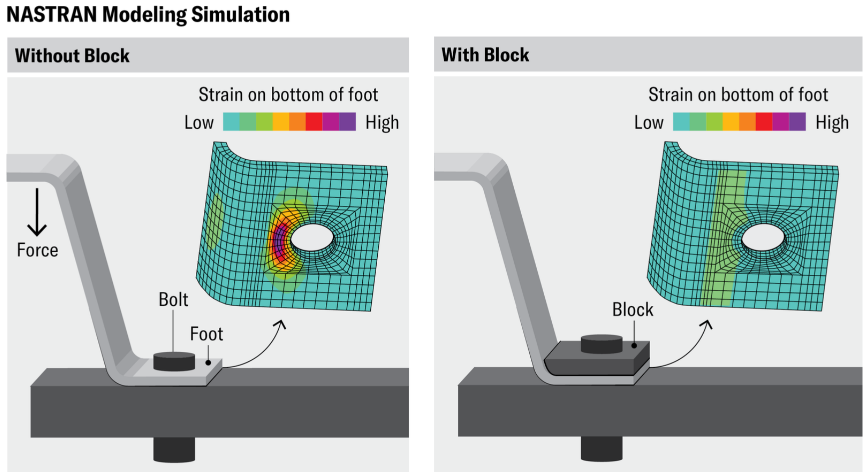
Three-dimensional objects can be similarly modeled; for these, the FEs are usually either blocks or tetrahedra, and the number of equations is typically much higher. For the modeling of an entire airplane, for instance, one might expect a problem with several million unknowns.

Although the FE method was originally developed to determine how structures behave when forces act on them, the technique is now seen as a general way to solve PDEs and is used in many other contexts as well. These include, for example, oncology (to track tumor growth), shoe manufacturing (to implement biomechanical design), film animation (to make motion more realistic, as in the 2008 Pixar movie *WALL-E*), and musical instrument design (to take into account the effect of vibrations in and around the instrument). Although FEs might be an unfamiliar concept to most people, one would be hard-pressed to find an area of our lives where they do not play a role.

Several applications involve the modeling of cracks. For instance, the authors of a 2018 study used FEs to explore how cracks propagate in teeth and what restorations might work best. In a different study, scientists investigated what kinds of femur fractures one can expect osteoporosis to lead to at different ages. FE simulation also helps to reveal the root cause *after* failures occur, as with the Florida condo collapse and the *Titan* implosion, and it is routine after aircraft accidents.

Drawing on their accumulated experience, engineers Richard H. MacNeal, John A. Swanson, Pedro V. Marcal, and others released several commercial FE codes in the 1970s. The best known of these “legacy” codes was originally written for NASA in the late 1960s and is now referred to as the open-source NASTRAN (short for “NASA Structural Analysis”). NASTRAN remains the go-to program for a crucial step in aeronautical design, in which engineers do a rough FE analysis of a computer model of the entire plane being designed to identify areas and components where structural problems are most likely to occur. These regions and parts are then individually analyzed in more detail to determine the maximum stress they’ll experience and how cracks may grow in them.

Questions such as whether a bolt may fracture or a fan blade may break off are answered at this individual level. Almost all such local analysis involves the legacy programs launched several decades ago, given their large market share in commercial settings. The design of the finished parts that end up in the aircraft we fly in or the automobiles we drive depends heavily on these codes. How accurate are the answers engineers are able to get from them? To find out, we need to take a deeper dive into the math.



Jen Christiansen; Source: “Stress Analysis and Testing at the Marshall Space Flight Center to Study Cause and Corrective Action of Space Shuttle External Tank Stringer Failures,” by Robert J. Wingate, in *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference Proceedings*, April 2012 (*reference*)

Earlier, we learned how to determine the deformation of our FE model for the screen, but how close will this result be to the true deformation? A remarkable theorem, first noted by French mathematician Jean Céa in his 1964 Ph.D. thesis but rooted in the work of Russian mathematician Boris G. Galerkin, helps to answer that question. The theorem states that as long as we minimize potential energy, out of all possible deformations our FE screen can assume, the one calculated by our method will be the closest possible to the exact answer predicted by the PDEs.

By the early 1970s several mathematicians worldwide had used Céa’s theorem to prove that the difference between the FE model’s predictions and the real shape would decrease to zero as the meshes became increasingly refined, with successively smaller and more numerous elements. Mathematicians Ivo Babuška and A. Kadir Aziz, then at the College Park and Baltimore County campuses of the University of Maryland, respectively, first presented a unified FE theory, incorporating this and other basic mathematical results, in a landmark 1972 book.

But around the same time mathematicians began discovering that engineers were incorporating various modifications and “tricks” into commercial codes, which, though often violating the crucial property of energy minimization, empirically seemed to work. Mathematician Gilbert Strang of the Massachusetts Institute of Technology named such modifications “variational crimes” (“variational” comes from the calculus of variations, which is related to the FE method). Mathematicians could prove that some of these “crimes” were benign, but others had the potential to produce substantially incorrect answers.

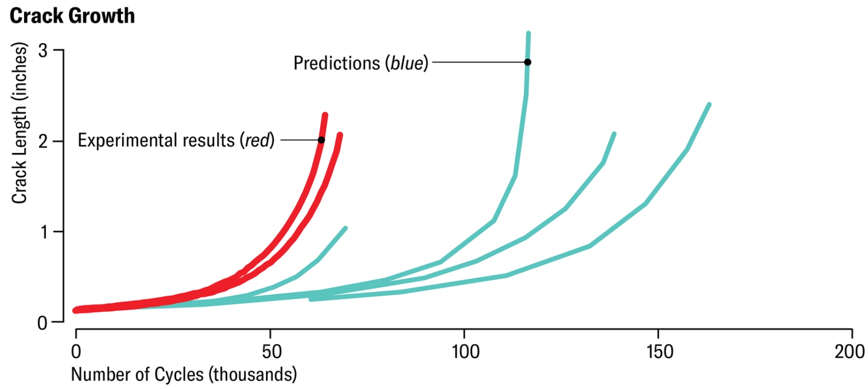
Particularly problematic were the work-arounds used to treat a breakdown in accuracy called locking. This issue arises when the underlying elasticity equations contain a value that is close to being infinite—such as a fraction in which the thickness of an extremely thin metal plate is used as the denominator. Locking also commonly occurs in models for rubber because an elasticity value related to Hooke’s law gets very large. It was only in the 1990s that Babuška and I provided a precise definition and characterization of locking. By then several other mathematicians, most notably Franco Brezzi of the University of Pavia in Italy, had, for many problems, established which variational crimes used to deal with locking are sound and which should be avoided because they can potentially give inaccurate answers.

But all this analysis had little effect on legacy codes, where risky modifications remain. One reason is that these codes were already entrenched by the time mathematicians recommended changes, so it was impractical to incorporate them. Also, there seems to be a gap between mathematical predictions and actual practice —“shades of gray,” as Thomas J. R. Hughes, a professor of aerospace engineering at the University of Texas at Austin, puts it. “Some mathematically suspect modifications can perform better than approved ones for commonly encountered problems.”

Perhaps the biggest hurdle to incorporating safer solutions to locking was a cultural difference between the mathematical and engineering views of FE modeling. Mathematicians see the FE solution as one in a series of approximations that, under appropriate mathematical conditions, are guaranteed to converge to the exact solution. In engineering practice, however, FE modeling is a free-standing design tool that tells you how the actual object will behave when built. Rank-and-file engineers commonly learn about FEs in a couple of courses at best, typically with no mention of such things as problematic modifications. Hughes relates an anecdote in which a modeling company refused to buy a newer software product because its results did not match the answer given by NASTRAN. The clients insisted the NASTRAN solution was exact and correct. (It was only by reverse engineering the new software that its designers got it to produce answers are matching NASTRAN's)

FE solutions can in fact be very different from the physical results they’re supposed to predict. The reasons include variational crimes, the limitations of underlying mathematical models, the exclusion of smaller features from simulations and the use of finite problems to replace the infinite one of solving a PDE. This is the case, for instance, in the preliminary analysis of large airplane components such as fuselages and wings. Engineers have to use past experimental results to “tune” the FE output before they can figure out what the true prediction is. Such accumulated wisdom is essential in interpreting FE results for new designs that haven’t yet been physically tested.

The strength analysis of smaller parts, such as lugs and fasteners, can present more of a problem because there are often no physical data available to tune things with. A 2022 challenge problem involving crack analysis, circulated by a major aerospace company to four contracting organizations that use legacy codes, found that the results from three groups diverged strikingly from the true, experimentally determined solution. The computations showed a crack growing much more slowly than it actually did, leading to a predicted safety margin that was disconcertingly inflated.



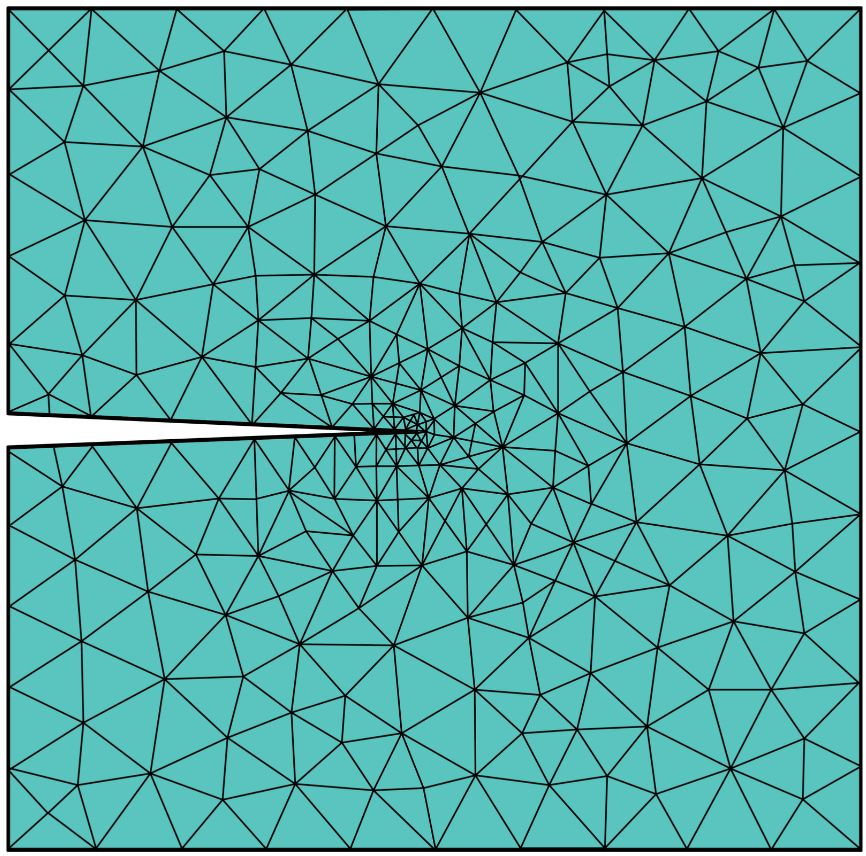
Jen Christiansen; Source: “The Demarcation Problem in the Applied Sciences,” by Barna Szabó and Ricardo Actis, in *Computers & Mathematics with Applications*, Vol. 1632; May 2024 (*data*)

Other such challenge problems have shown that inaccurate codes are not necessarily the core issue—participants often made simplifying assumptions that were invalid or selected the wrong type of element out of the multitude of available variations of the original triangle and quadrilateral. Such errors can be expensive: the 1991 collapse of the Norwegian oil platform mentioned earlier caused damages amounting to more than $1.6 billion in today’s dollars. Simulation shortcomings have also been implicated in the F-35 fighter plane’s many fatigue and crack problems, which have contributed to its massive cost overruns and delays. In general, the less certainty one can ascribe to computational results, the more frequently expensive inspections must be carried out.

The problem of estimating how reliable a simulation is might seem hopeless. If we don’t know the exact solution to our computer model of, say, an airplane component, how can we possibly gauge the error in any approximate solution? But we *do* know something about the solution: it satisfies the partial differential equations for the object. We cannot solve the PDEs, but we can use them to check how well a candidate solution works—a far easier problem. If the unknown exact solutionwere plugged into the PDE, it would simply yield 0. An approximate solution will instead give us a remainder or “residual,” typically called *R*—a measure of how good the solution is.

Further, because the object is being modeled by finite elements that can deform only in certain ways, the calculated stresses will not vary smoothly as they do in reality but jump between the boundaries of the elements. These jumps can also be calculated from the approximate solution. Once we compute the residuals and jumps, we can estimate the error across any element using techniques that Babuška and Werner C. Rheinboldt of the University of Pittsburgh, along with other mathematicians, started developing in the late 1970s. Since then, other strategies for estimating the errors of FE analyses have also been developed.

Estimating the error has several benefits. First, because the inclusion of smaller and more numerous elements generally improves the accuracy, you can program your code to automatically generate, in successive steps, smaller elements in regions where the error is likely to be large. We already saw from the mathematical analysis of PDEs that the stresses increase very rapidly near corners and edges. This phenomenon also makes the error highest in such regions. Instead of manually creating finer meshes in such critical locations, this step can be taken care of automatically.



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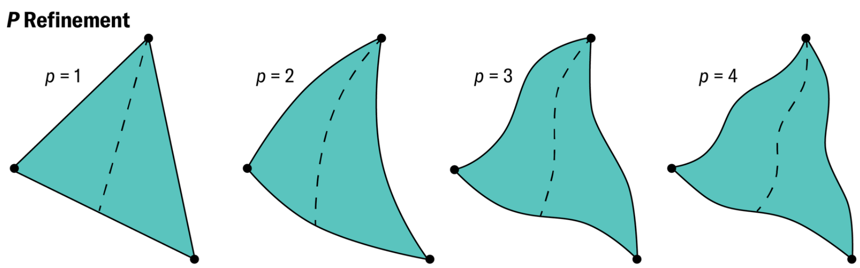
Second, the estimated overall error can help engineers gauge how accurate the calculated values are for quantities they're interested in, such as the stress intensity in a critical area or the deformation at a particular point. Often engineers want the error to be within a certain margin (from less than 2 to 10 percent, depending on the field). Unfortunately, most algorithms overestimate or underestimate the error, so it is difficult to say how good the boundthey provide really is. This aspect remains an active area of research. Even so, error estimation, had it been used, almost certainly would have alerted engineers about the problem with their FE model for the Norwegian oil platform.

A better way to estimate overall error—that is, to assess the reliability of a computed solution—is to use a different philosophy for the FE method: the so-called *p* refinement, first developed by engineer Barna Szabó of Washington University in St. Louis in the 1970s. The usual way to increase accuracy is called *h* refinement because the mesh is successively refined through reduction of a typical element's width, denoted by *h*. For *p* refinement, we stick with just one mesh throughout but increase accuracy by allowing each triangle to deform in additional ways instead of always remaining flat. In the first step, the method allows a straight line in any triangle to bend into a parabola, and then, step by step, lines transition into ever more complex curves. This modification gives each element increasing wiggle room, allowing it to match the shape of the solution better at each step. Mathematically, this process amounts to increasing the degree *p* of the underlying polynomials, the algebraic formulas used to denote different types of curves.



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As Babuška and his colleagues, including me, have shown, *p* refinement converges to the exact solution of the PDEs faster than the traditional *h* method for a wide class of problems. I have also helped prove mathematically that the *p* version is free of locking problems, so it doesn't need any of the modifications used for the *h* method. Further, the succession of wiggling shapes turns out to offer an easy and dependable way to assess reliability.

Discouragingly, however, neither the *p* nor the *h* method of assessing reliability plays a prominent role in the legacy codes from the 1970s used to this day. The reason might be that the programs were designed and became culturally entrenched before these advances came along. Among newer industrial codes, the program StressCheck is based on the *p* version and does provide reliability estimates.

Such estimation offers a further benefit when experimental results are available for comparison: the ability to assess the difference between physical reality and the PDEs used to model it. If you know the FE analysis is accurate but your overall error is still large, then you can start using more complex models, such as those based on physics where proportionality no longer holds, to bridge the gap. Ideally, any underlying mathematical model should be validated through such comparisons with reality.

The advent of artificial intelligence most likely will change the practice of computer simulation. To begin with, simulation will become more widely available. A common goal of commercial AI programs is to "democratize" FE modeling, opening it up to users who might have little intrinsic expertise in the field. Automated chatbots or virtual assistants, for instance, can help guide a simulation. Depending on how thoroughly such assistants have been trained, they could be a valuable resource, especially for novice engineers. In the best case, the assistant will respond to queries made in ordinary language, rather than requiring technical or formatted phrasing, and will help the user choose from the often dizzying array of elements available while giving adequate alerts about mathematically suspect modifications.

Another way AI can be effective is in generating meshes, which can be expensive when done by a human user, especially for the fine meshes needed near corners, crack tips, and other features. Mathematicians have determined precise rules for designing meshes in such areas in both two and three dimensions. These rules can be exceedingly difficult to input manually but should be fairly easy to use with AI. Future codes should be able to automatically identify areas of high stress and mesh accordingly.

A more nascent effort involves supplanting FE analysis entirely by using machine learning to solve PDEs. The idea is roughly to train a neural network to minimize the residual R, thereby constructing a series of increasingly accurate predictions of the displacements for a set of loadings. This method performs poorly with crack problems because of high localized stresses near the crack tips, but researchers are finding that if they incorporate information about the exact nature of the solution (by, for instance, using the mathematical work of Kondrat'ev), the method can be viable.

In the midst of these and other potentially game-changing AI initiatives, the decidedly unflashy task of assessing the reliability of computations, so crucial to all these advances, is not being sufficiently addressed. Stakeholders should look to NASA's requirements for such reliability. These include demonstrating, by error estimation and other means, that the underlying physics is valid for the real-life situation being modeled and that approximations such as FE solutions are within an acceptable range of the true solution of the PDEs.

NASA first codified these requirements into a technical handbook as a response to the *Columbia* space shuttle disaster. The prospect of human expertise and supervision dwindling in the future should be no less of a wake-up call. Dependable safeguards for reliability need to be built in if we are to trust the simulation results AI delivers. Such safeguards are already available thanks to mathematical advances. We need to incorporate them into all aspects of numerical simulation to keep aviation and other engineering endeavors safe in an increasingly challenging world.

Manil Suri is a professor of mathematics at the University of Maryland, Baltimore County, and author of the book *The Big Bang of Numbers: How to Build the Universe Using Only Math* (W. W. Norton, 2022).

Advanced Meditation Alters Consciousness and Our Basic Sense of Self

An emerging science of advanced meditation could transform mental health and our understanding of consciousness

By Matthew D. Sacchet & Judson A. Brewer

Anand Purohit/Getty Images

Millions worldwide practice mindfulness meditation, not just for their mental health but as a means to enhance their general well-being, reduce stress and be more productive at work. The past decade has seen an extraordinary broadening of our understanding of the neuroscience underlying meditation; hundreds of clinical studies have highlighted its health benefits. Mindfulness is no longer a fringe activity but a mainstream health practice: the U.K.'s National Health Service has endorsed mindfulness-based therapy for depression. Mobile apps have brought meditation techniques to smartphones, enabling a new era in meditative practice.

The approach to research on meditation has been evolving in equal measure. Looking back, we can identify distinct "waves." The first wave, from approximately the mid-1990s into the early 2000s, assessed meditation's clinical and therapeutic potential for treating a broad set of psychological and physical health concerns. The second wave, starting in the early 2000s, focused on mechanisms of mindfulness's effectiveness, revealing why it yields benefits for mental health that are at times comparable to those achieved with pharmaceuticals. Meditation science is now entering a third wave, exploring what we call advanced meditation—deeper and more intense states and stages of practice that often require extended training and can be experienced through increasing mastery. University research programs are being established to study these altered mental states, similar to new academic endeavors to investigate the merits of psychedelic drugs for personal well-being and a variety of medical conditions.

In the media and in academia, meditation is often seen as a tool primarily for managing the stresses of modern life and work. But our research suggests it can be used for much more. Although meditation can help people improve their psychological well-being, it also can be a gateway to experiences that lead to deep psychological transformation.

> The term "advanced meditation" might evoke images of monks in robes, but these experiences are not limited to ascetics isolated from the world.

People often come to meditation because of some kind of suffering. Others are drawn to it because they perceive a lack of meaning in the materialism of the modern world. Still others may feel a pull toward "something greater" when they realize that a self-absorbed pursuit of "happiness" has its limitations.

Meditation's potential has been demonstrated by numerous contemplative, philosophical, religious and spiritual traditions that teach it as a core element that leads to enlightenment or salvation. Buddhism, Vedic and Hindu practices, Jewish kabbalism, Islamic Sufism and shamanism, among others, have all explored meditation in their traditions. Some of them have multimillennia-long histories and encompass experiences that include states of ecstasy, insights into the nature of the self and the world around us, the cultivation of empathy, and the pursuit of altruistic goals. Such experiences have also been reported to sometimes lead to a sense of transcendence.

The experiences and personal transformations that practitioners describe are thought to undergird entirely new psychological perspectives and ways of existing in the world. Advanced meditation may help inspire people and provide deep insight and clarity about how to achieve meaning in life. It is not uncommon, in fact, for individuals to reassess their careers or life goals after a meditation retreat and go on to pursue a path that is more fulfilling and that is more aligned with their deeper values and perspectives.

The term "advanced meditation" might evoke images of monks in robes, but these experiences are not limited to ascetics isolated from the rest of the world. Laypeople who lead secular lives can become practitioners of advanced meditation and achieve a sense of profound well-being. In the new and emerging science of this third wave, advanced meditation includes deeper states and stages of meditation that a person may progress through with increasing mastery over time.

The study of advanced meditation examines meditative development—the unfolding of advanced meditative states and stages of practice. Then there is research on meditative endpoints, which represent the outcomes of advanced meditation. In Buddhist traditions, one outcome may be called enlightenment or awakening.

We believe that advanced meditation has potentially broad implications for people's understanding of what it means to be human and for interventions for mental health and well-being, and it therefore deserves the attention of the scientific community. One of us (Sacchet) leads an effort at Massachusetts General Hospital and Harvard Medical School named the Meditation Research Program, established to develop a comprehensive multidisciplinary understanding of advanced meditation states and stages of practice related to well-being and clinical outcomes (meditative endpoints). We use a rich array of state-of-the-art scientific approaches. Our intention is to expand the program into a much larger research and educational effort and establish the first center dedicated to the study and training of advanced meditation.

Another research endeavor on advanced meditation has been taking place at Brown University's Mindfulness Center (led by Brewer). Scientists there have discovered signatures of brain activity during several forms of meditation used in Tibetan Buddhism that are able to produce feelings of timelessness and states of heightened awareness. Research on advanced meditation is also taking place elsewhere and is expected to grow rapidly in the coming years.

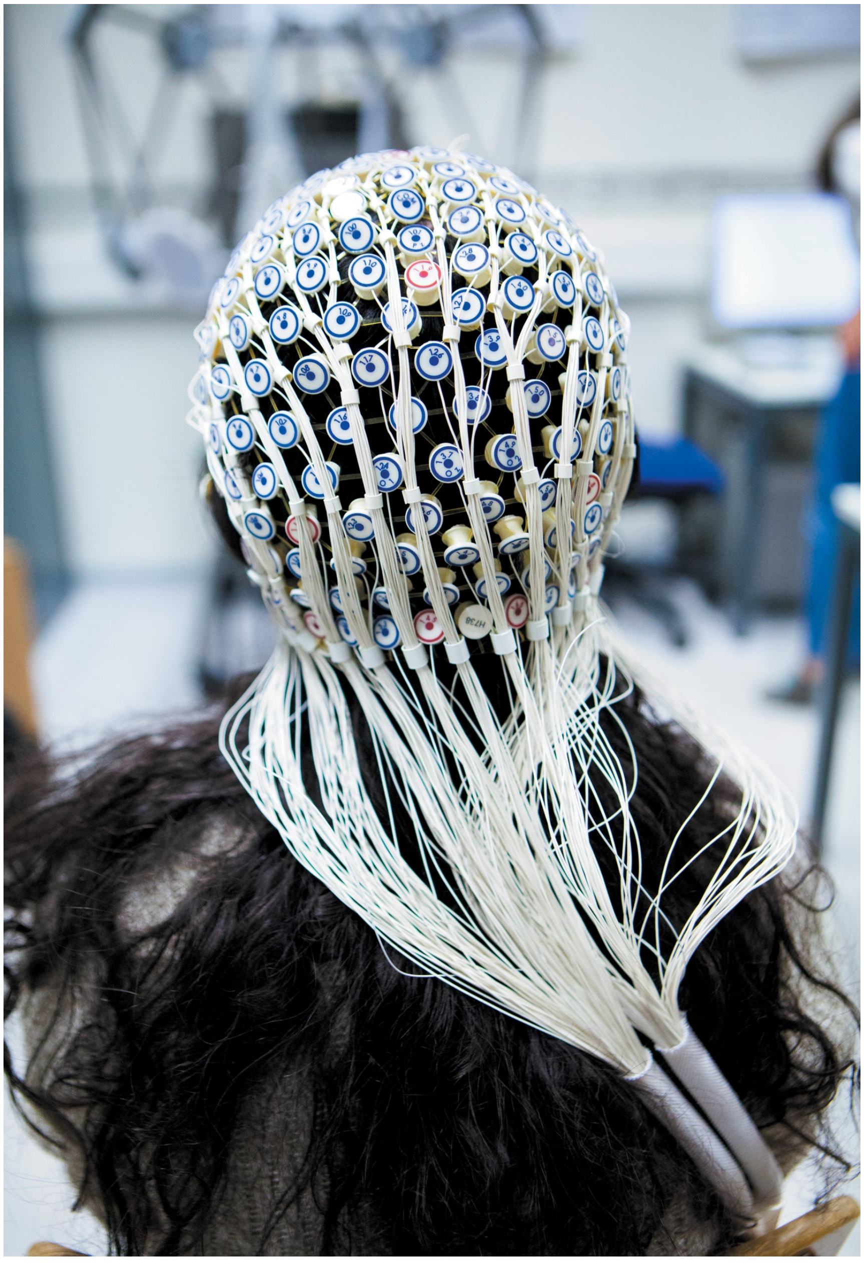
All of these investigations promise to help us find new ways to train people in advanced meditation. We envision developing specific programs that leverage insights from the science of advanced meditation to directly train people with certain clinical diagnoses. These programs could offer new therapeutic avenues for treating persistent cycles of negative thoughts in patients with major depression or the chronic worrying that characterizes generalized anxiety disorder. The idea is not just to manage symptoms but to foster a sense of deep and pervasive well-being that affects all aspects of a practitioner’s life.

Our findings are starting to inform models of how advanced meditation affects and changes the brain, paving the way for a more comprehensive grasp of these practices. In time, our research may lead to a new generation of mental health interventions that could be as simple as a set of verbal instructions or as technologically sophisticated as neurofeedback or brain stimulation.

Advanced meditation lends itself to modern, empirical scientific study for several reasons, one of which is the robust research foundation provided by decades of studies from the prior waves. This research included initial attempts to characterize the brain activity of experienced meditators. Notable examples can be seen in the seminal work of teams led by Richard Davidson of the University of Wisconsin–Madison and Sara Lazar of Massachusetts General and Harvard Medical School. Their work with long-term meditators included electroencephalography (EEG) and the first magnetic resonance imaging study of brain activity in such practitioners. A major limitation of this early research, however, was that it did not explore the rich firsthand descriptions of what people experience during advanced meditation, encompassing states of mind in which consciousness itself may vanish.

The latest wave of research coincides with a broader surge of interest in altered states of consciousness, including those studied in psychedelic research. From a technical perspective, the study of advanced meditation has been facilitated by the recognition that certain altered states can be induced at will by adept practitioners. Advanced meditation, once considered on the scientific fringe, has now made it possible to scientifically understand practices previously limited to monks and mystics.

Our team at Massachusetts General and Harvard’s Meditation Research Program has begun to integrate advanced meditation into rigorous experimental paradigms using cutting-edge methods such as neuroimaging. Studying the neural activity of practitioners in deep meditative states is important because it provides evidence for the biological existence of these states—a first step toward understanding and gaining widespread access to advanced meditation and its benefits.



An array of electrodes can be used for electroencephalography (EEG) to study electrical activity in the brains of advanced meditators.
BSIP/Getty Images

To cite one example, our group at Harvard recently conducted a study on the experiences and neuroscientific underpinnings of what we have classified as advanced concentrative absorption meditation (ACAM), one form of which is *jhāna* from Theravada Buddhism. Practitioners of *jhāna* report unfettered calmness, clarity of mind and self-transcendence (going beyond the concept of the self and perceiving diminishing boundaries between oneself and others). They also usher in open consciousness, a state of mind that is receptive, adaptable and accepting of perspectives beyond the existing narrative that shapes how someone sees the world.

To investigate these states, we used a powerful, seven-tesla MRI machine at Massachusetts General—a first in meditation research. Seven-tesla MRI lets us map the entire brain at high resolution. Its deep-brain imaging extends to the brain stem and cerebellum, areas crucial for healthy mental and physiological functioning that are difficult to study with conventional MRI at lower magnetic field strengths. Brain stem activity, which controls breathing and heart rate, is a prerequisite for consciousness and alertness, so it was a primary target for our work.

Our aim was to create a detailed map of the brain's activity during ACAM and link it to the meditator's reported experiences. We conducted an intensive case study of ACAM spanning 27 MRI data-collection periods that were completed over the course of five days. The case study was of a meditator who had more than 25 years of experience with ACAM and had completed more than 20,000 hours of meditation. We identified distinctive patterns of brain activity in the cortex, subcortex, brain stem and cerebellum regions that were active during ACAM.

Furthermore, we observed correlations between brain activity and certain qualities of ACAM related to attention, joy, mental ease, equanimity, narrative processing (the organization of information into a structured story), and formlessness (in which the sensation of inhabiting the body completely falls away). We also highlighted the distinct nature of brain activity during ACAM compared with that in several nonmeditative states. We found that patterns of local activity across brain regions were unique during advanced concentrative absorption meditation and that they were different from those we observed during ordinary states of consciousness.

> After a cessation event, the practitioner undergoes a profound shift in mental perspective and well-being, including deep mental clarity and a sense of renewal.

In another study, conducted at the University of Massachusetts's Center for Meditation, researchers employed EEG to investigate 30 advanced meditators using practices from the Tibetan Buddhist tradition. Four advanced meditation states were characterized by self-transcendence, emptiness (a state of awareness beyond the mind's constant word patter) and compassion. This study, on which Brewer was the senior researcher, is important in part because these characteristics are associated with psychological well-being and are disrupted in people with certain mental illnesses. The results indicated that the density of EEG currents was lower during advanced meditation. This effect was strongest in brain regions involved in self-referential processing (self-related mental activities)and executive-control regions. There is some evidence that advanced meditation practices may dampen self-referential processes and reduce the mind's focus on the self.

We found from this research that a deeper meditation state was associated with increases in high-frequency brain activity in the anterior cingulate cortex, precuneus and superior parietal lobule and with elevation of the beta-band brain wave in the insula. Together, these results provide initial evidence for specific electrophysiological markers relevant to advanced practices. These brain-activity signatures have particular relevance to non-self-referential states advanced meditators can attain, known as nondual states. This study is also notable because it is an example of research on advanced meditation informed by Tibetan Buddhism. It will be a crucial development for the field to compare advanced meditative states among diverse contemplative traditions that historically have been separated geographically, culturally and philosophically.

In a third study, our Harvard/Massachusetts General team investigated, for the first time, what are called cessation events. We used EEG combined with a novel investigative approach that involves the meditators' description of their own experiences, with the goal of finding a neural signature of these advanced meditation experiences. Cessations are radically altered states characterized by a full loss of consciousness. They are thought to result from deep mastery of a mindfulness-based meditation that is part of the *vipassana* tradition in Theravada Buddhism.

When we discuss the loss of consciousness during advanced meditation cessation events, it is crucial to differentiate it from unconsciousness that is caused by anesthesia, coma (including medically induced coma), physical trauma such as head injuries, and naturally occurring events such as sleep. Unlike these states, cessation events in advanced meditation represent a peak meditative experience in which ordinary self-awareness and sensory processing are temporarily suspended.

After a cessation event, the practitioner undergoes a profound shift in mental perspective and well-being, including deep mental clarity and a sense of renewal. In Theravada Buddhism, these events are known as *nirodha* and represent an important meditative endpoint.

For our study, we examined cessations experienced by a single advanced meditator with more than 23,000 hours of meditation training. We analyzed EEG data for 37 cessation events recorded during numerous sessions. Immediately after each EEG run, the participant graded different qualities of any cessations that had occurred. We used a unique approach in which we tied the practitioner's first-person descriptions of the meditation experience to our objective neuroimaging data. We found that specific EEG signatures—notably, one called alpha spectral power and another called alpha functional connectivity—started to decrease approximately 40 seconds before a cessation and returned to normal about 40 seconds after it ended.

The lowest levels of alpha power and connectivity occurred immediately before and after cessation. The results of this study are consistent with the suggestion that this type of meditation diminishes hierarchical predictive processing—that is, the mind’s tendency to predict and rank self-related narratives and beliefs. The cessation process can ultimately result in the absence of consciousness and the emergence of a deeply present form of awareness and thought that accepts whatever arises, whether positive or negative. Our findings provide preliminary insight into the mechanisms underlying the highly unusual capacity to induce a momentary lapse of consciousness during cessations, suggesting it involves measurable changes in brain activity.

Much like psychedelics, advanced meditation is sometimes linked to challenging psychological disturbances, so it needs to be practiced along with the guidance of properly skilled practitioners. Initial forays into the science of advanced meditation we’ve described here lay the groundwork for further investigation. One of our objectives is to achieve a scientific understanding that facilitates broader accessibility to these practices. Like simpler forms of mindfulness meditation, advanced meditation can be practiced in diverse settings, when seated on the floor or a chair, with eyes open or closed.

Advanced meditation holds remarkable promise for supporting well-being in both clinical and nonmedical settings. This domain of meditation has the potential to massively reduce or otherwise alter narrative and self-referential thinking, improve attention, and foster feelings of self-generated joy and contentment far beyond what is currently understood in the domain of “mindfulness” research and practice—qualities that are often difficult for people with mental health conditions to attain. Mindfulness meditation has indeed helped millions of people, but advanced meditation research could revamp the field of mental health, offering entirely new avenues for the treatment of psychiatric disorders and, more generally, fostering a sense of well-being.

Evidence is growing for the efficacy of psychedelics as treatments for some psychiatric conditions, especially depression and post-traumatic stress disorder. We think that people can make similar progress through meditation. Future research may benefit from examining how ACAM and other forms of advanced meditative states relate to psychedelic experiences and how they may similarly help to alleviate symptoms of psychopathology.

Advanced meditation interventions could be integrated with established mindfulness-based techniques, novel meditation-based therapies, and innovative technologies designed to modulate specific neural networks through neurofeedback and brain stimulation. These methods may make it possible for people to have the experience of an advanced meditative state without undergoing extensive training.

Advanced meditation therefore holds significant and untapped opportunities to diminish suffering and help people flourish. It may even provide a gateway to entirely new ways of understanding our basic humanity.

As interest in meditation continues to grow, so does the potential to explore its full spectrum of possibilities for bettering the mental and physical health of individuals and society. Our work in the new wave of advanced meditation research is not just about coping with the stress of modern living. It could improve our understanding of and approach to the mind, mental health and well-being, allowing each of us to lead a more fulfilled, compassionate and "enlightened" life.

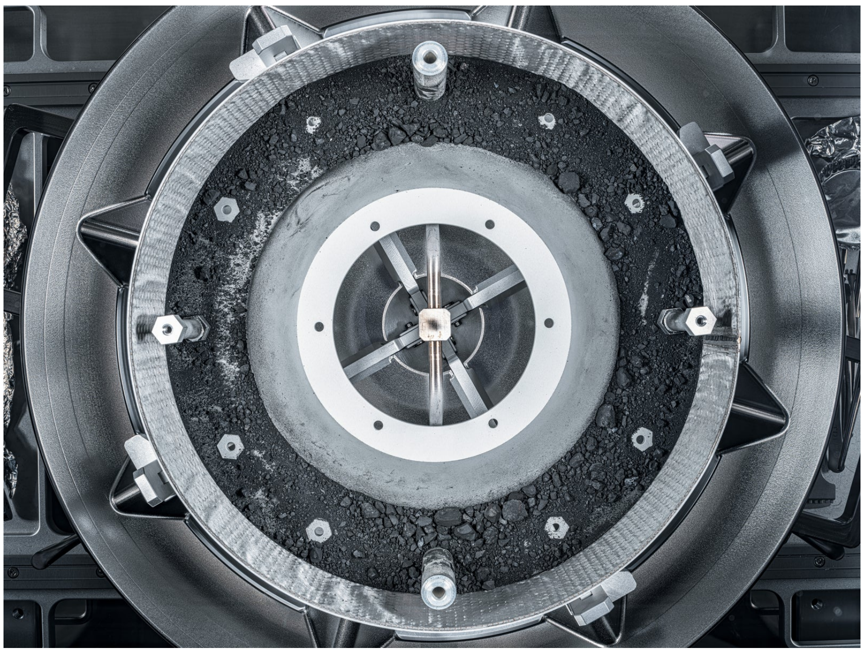
Matthew D. Sacchet is an associate professor and director of the Meditation Research Program at Harvard Medical School and Massachusetts General Hospital.

Judson A. Brewer is a professor and director of research and innovation at the Mindfulness Center at the Brown University School of Public Health.

NASA’s New Asteroid Sample Is Already Rewriting Solar System History

Scientists have scarcely begun studying pristine material from asteroid Bennu that was brought back to Earth by the OSIRIS-REx mission, but they have already found several surprises

By Robin George Andrews



A top-down view of the contents of the OSIRIS-REx sample-return capsule.
NASA/Erika Blumenfeld and Joseph Aebersold

Meteorites are messengers from the depths of time—cast-off fragments of asteroids and comets that formed alongside our sun from raw materials predating our star. But their messages are often muddled by their final encounter with Earth—charred in their fiery plunge through our planet’s atmosphere and contaminated by our world’s ever shifting environment. And unlike a typical piece of lost mail, they don’t come with a return address to reveal their provenance. But what if the scientists wishing to be historians of our solar system’s earliest days could sidestep these problems? Rather than relying solely on the random, scattered chapters of cosmic history meteorites contain, wouldn't it be better to directly visit space's most ancient archives—the asteroids and comets—to bring back entire geological books to read?

NASA's Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft did just that in 2020, when it dove down to the surface of the near-Earth asteroid Bennu and retrieved some rocks dating back at least 4.5 billion years. Last September it returned to Earth to drop them off. It's not the first (or second) spacecraft to burgle an asteroid. But it brought back the largest sample to date: a whopping 121.6 grams of pristine material from the solar system's dawn.

Almost immediately after the sample-return capsule landed on Earth, scientists began their forensic examinations. And earlier this year they presented their first in-depth findings for all the world to see. Their analyses are preliminary, but it seems that Bennu's original form was shockingly familiar. Billions of years ago Bennu was apparently part of a water-soaked world, one with a beating geological heart and an abundance of prebiotic organic material, now long lost. In many respects, this nameless world could have borne a passing resemblance to the early, lifeless Earth. "Bennu literally carries the building blocks of life within its minerals," says Louisa Preston, an astrobiologist at University College London.

> Billions of years ago Bennu was apparently part of a water-soaked world, one with a beating geological heart and an abundance of prebiotic organic material.

Firmer conclusions are still to come, but already it’s clear that these precious pieces of Bennu harbor immense potential. “What we’re trying to do with these samples is understand how Earth was formed—not just its water, not just its prebiotic compounds, but how Earth itself formed,” says Harold Connolly, a geologist at Rowan University and mission sample scientist for the OSIRIS-REx project.

And it’s not all about our blue-green marble. Some of the sample’s microscopic grains reveal that Bennu’s odyssey began before our sun’s first fires burned, meaning planetary scientists can use it to help answer one of their field’s most monumental queries. “What was that starting mineralogy of the solar system? Where did that dust come from? Did it all come from just one star or multiple generations of stars or different types of stars?” says Ashley King, a meteoriticist at London’s Natural History Museum and an OSIRIS-REx team member. Thanks to the mission’s daring raid on Bennu’s archives, “we’re putting that all together,” Connolly says.

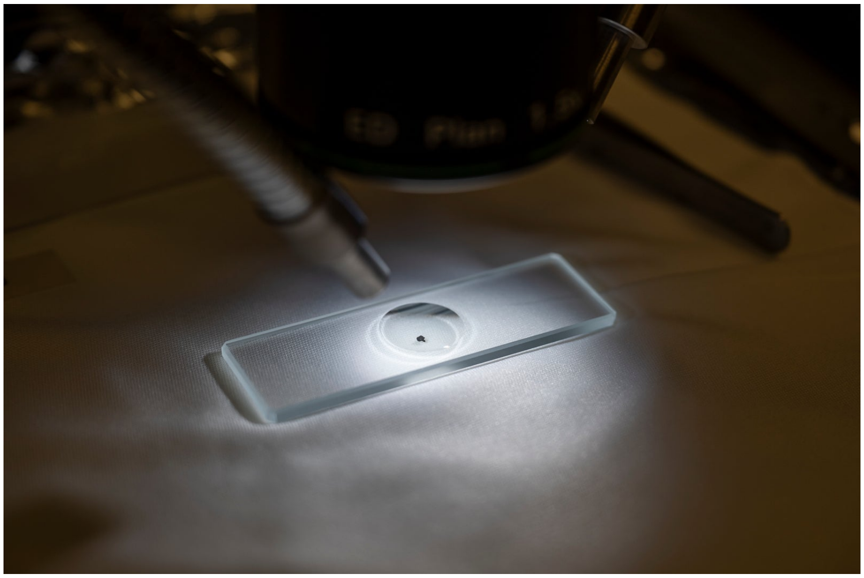
The “Origins” in OSIRIS-REx’s full name refers to the genesis and history of Bennu as a proxy for all other carbon- and water-rich asteroids that have circled the sun these past few billion years. It’s a mammoth undertaking. “We’ve looked at 1 percent of the sample” so far, Connolly says. But this amount is sufficient to begin testing a wish list of hypotheses the team has about Bennu’s life.

A key question: What went into making Bennu’s original (or “parent”) body? Clues reside within its presolar grains, crystals that condensed before the sun existed—“basically, the building blocks of our solar system,” says Pierre Haenecour, a cosmochemist at the University of Arizona and an OSIRIS-REx team member. So far they’ve identified at least two broad categories of presolar grains.

Plenty have the chemical signatures of intermediate- to low-mass stars that were in the latter stages of their life; such stars produce potent stellar winds as they age, expelling much of their atmosphere into deep space to create clouds of gas and dust that can be recycled into newborn stars. Other grains hint at a more violent origin. “We do have some presolar grains that appear to have compositions more consistent with what we find in supernovae,” Haenecour says. Altogether these details support the long-standing suspicion that our solar system was seeded and enriched by the explosive deaths of a diverse range of thermonuclear furnaces.

Not long after our sun emerged, worlds began to coalesce around it under gravity’s influence, including Bennu’s unknown parent body. Bennu may exist as a midsize asteroid in a near-Earth orbit today, but the team suspects that eons ago its water-loaded parent first took shape beyond the snow line—a diffuse thermal circumstellar boundary that determines where more volatile substances, including water, can exist as ice around a star.

There is no agreement yet on just how far out Bennu’s protoworld formed. One hypothesis holds that it was not in the asteroid belt between Mars and Jupiter but somewhere farther afield. Key to testing that notion will be the absence or presence of various ices and their residue within the sample. Water ice can exist close to the sun, including within the asteroid belt, whereas frozen carbon monoxide starts to vaporize at a greater distance from it—somewhere in the realm of Neptune.



Sourced from a 121.6-gram sample returned to Earth by NASA's OSIRIS-REx spacecraft, a small speck of material from the asteroid Bennu sits on a prepared microscope slide in an exhibition at the Smithsonian's National Museum of Natural History in Washington, D.C.
NASA/Keegan Barber

The array of temperamental chemicals already found in the sample is “consistent with an outer-solar-system origin,” says Kelly Miller, a cosmochemist at the Southwest Research Institute in San Antonio, Tex. Intriguingly, the detection of a soupçon of ammonia, an extremely volatile substance, was also announced at the conference. This could be associated with the asteroid’s organic matter. But if it came from ammonia ice, then “that would push [Bennu’s parent body] out even farther into the outer solar system,” Connolly says—perhaps in or beyond the realm of the ice giant planets Uranus and Neptune.

Wherever Bennu’s parent body formed, it was certainly not in stasis. The sample appears to be packed with clays and other mineral assemblages that are clear signs of dynamic transformations, such as being saturated in liquid water or even having some of that water evaporate to leave behind salts. “Bennu is dominated by materials that are altered by water,” says Sara Russell, a planetary scientist at London’s Natural History Museum and an OSIRIS-REx team member.

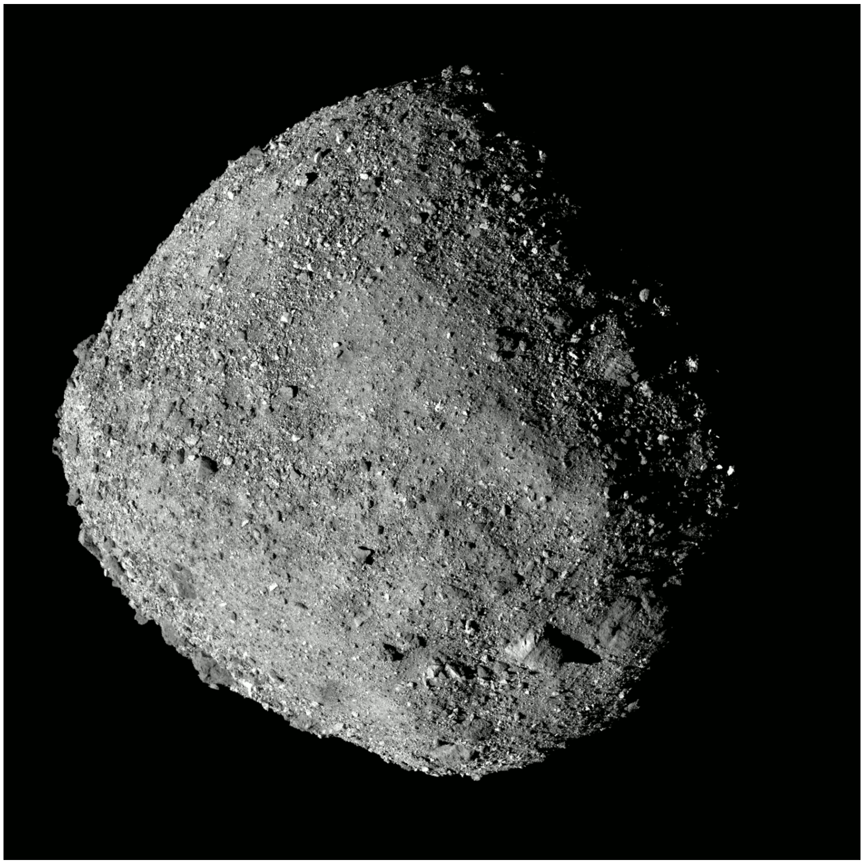
Although the water wasn't scorching hot, it was certainly warm, and its composition might have evolved over time, which suggests that multiple hydrothermal systems were driven by melting ice. That ice melted, at least for a few million years, because the parent body had a toasty geological core heated by the decay of radioactive isotopes. This information indicates that Bennu's precursor was at least 10 kilometers wide, perhaps larger, Connolly says.

"It's a beautiful sample," Russell says. "It's also not quite like any meteorite in our collection." For the time being, there appears to be nothing else quite like Bennu, which makes interpreting its mineral makeup a troublesome task—and one aspect of its chemistry in particular has sparked intense debate.

In February the mission team announced the surprising presence of phosphates in the sample. Underneath the icy carapace of Saturn's moon Enceladus, a geologically tumultuous orb, is a warm liquid-water ocean that contains a range of ingredients essential to life, including phosphorus compounds. After finding phosphates within the Bennu sample, OSIRIS-REx principal investigator Dante Lauretta speculated that the asteroid "may be a fragment of an ancient ocean world."

"I'm not willing to go there yet, because we haven't teased out enough of the petrology and petrography to put the story together," Connolly says. But Bennu is decorated with features that may be linked to surprising geological activity. One of the rock types the spacecraft observed on Bennu looks "cauliflowerlike," Connolly explains—a smashed-up, squashed-together mess of a sediment-packed rock "that is typically formed in subduction zone areas" akin to those found at Earth's continental margins and in deep-sea basins. The thought of Bennu's precursory world having an Earth-like shifting and tumbling of tectonic slabs is tantalizing, to say the least. But these rocks are chaotic and difficult to interpret. "It doesn’t mean that the parent body was tectonically active,” Connolly says.

Currently most scientists are envisioning not so much a geologically hyperactive world as a waterlogged rock with a dynamic youth. “I like to think of it as a big mudball,” King says.



An animation showing the rotation of near-Earth asteroid Bennu, captured over a four-hour period on December 2, 2018 by NASA's OSIRIS-REx spacecraft.
Credit: NASA/Goddard/University of Arizona

That mudball eventually ended up in the asteroid belt, perhaps after being yanked out of a more distant orbit by the gravitational pull of Jupiter. One working hypothesis is that after about three billion years, this parent body was destroyed by a catastrophic collision, liberating the shard we now call Bennu, which then made its way into near-Earth space. That inward migration speaks to a key chapter in the history of the solar system: the delivery of water and prebiotic organic material—carbon-based compounds used by biology—to rocky worlds.

“It’s a long-standing question: Where did Earth’s water come from?” says Richard Binzel, an asteroid expert at the Massachusetts Institute of Technology and an OSIRIS-REx co-investigator. “For a long time we thought it [came from] comets because they’re the most water-rich things we see.” But in recent years analyses of water ice on various comets have revealed its chemical fingerprints to be quite different from those of the water that fills Earth’s oceans.

Conversely, the water found within myriad soggy meteorites is a far closer match to that in our planet’s reservoirs. And what of Bennu? That grand reveal is still some time away, but regardless of whether Bennu has Earth-like water, that perennial query won’t be definitively answered—Earth’s seas and oceans were probably procured from diverse cosmic sources. It’s also possible that their creation wasn’t reliant on asteroids at all; rather Earth’s oceans might have been enclosed within the planet as it formed before escaping to the surface via ancient volcanism.

Then there are the organic compounds. “Biology started off life as chemistry,” Preston says. Even in the exceedingly unlikely event that the OSIRIS-REx sample harbors fossilized alien microorganisms, Bennu won’t provide any concrete answers as to how life got started on Earth. But life couldn’t exist at all without a suite of carbon-bearing compounds such as amino acids. One idea is that these formed in the spaces between the stars before asteroids like Bennu brought these ingredients to our planet.

“We know [that asteroids] can deliver these things to Earth. But the key step is: How did they become life? We need to know that inventory to be able to answer that,” King says. Already the team has identified a long list of organic molecules, including a suite of amino acids, present in the sample. “They even found uracil and thymine—uracil being one of the four nucleotide bases used in RNA and substituted by thymine within DNA,” Preston says. Some of these vital-to-life substances also have primeval inceptions.

“Bennu contains organic matter that formed in the interstellar medium,” Ann Nguyen, a planetary scientist at NASA and an OSIRIS-REx co-investigator, said during a conference presentation.

Not all astrobiologists are fixated on amino acids. “I might be a bit of a heretic,” says Cole Mathis, an astrobiologist at Arizona State University, but he isn’t especially interested in abundances of organic matter in Bennu. “It’s not hard to make amino acids,” he says—if you combine nitrogen, carbon and oxygen, “these things are more or less unavoidable.” Asteroids might have delivered them to Earth, but much like the planet’s water, these compounds easily could have formed on Earth without requiring a Bennu-like delivery.

Mathis wants to use Bennu to explore the boundary between chemistry and biology. “There are some molecules that are so complex that only life could have made them,” he says, offering vitamin B_{12} as an example. He isn’t expecting anyone to find anything like that in the sample. But he wants to find out which molecules can be made by both life and abiotic chemistry and which can be made only by life. “Where should that transition be?” he asks. Bennu, he hopes, will offer hints as to where this boundary lies—because the more baroque an organic compound is, the trickier it is for chemistry alone to make it. Mathis’s query, then, is not about abundance but about chemical convolution: “What’s the most complex individual molecule we can find in these materials?”

Answers to this question and many others are forthcoming. They are hidden within a small pouch of pristine asteroid material awaiting interrogation. Those grains might have cost $1.2 billion to bring to our planet, but they are effectively priceless because they can add context to that famous aphorism: “We are all stardust.” Scientists are now beginning to learn the exact nature, and provenance, of this stardust—the stuff that went into making everything we see, including Earth and ourselves.

Hopes were high when OSIRIS-REx scooped up that sample from Bennu. Already they’ve been surmounted. “The universe was smiling on us,” Connolly says.

Robin George Andrews is a volcanologist and science writer based in London. His first book, *Super Volcanoes*, was published in November 2021; his next, *How To Kill An Asteroid*, will be out later this year (both published by W.W. Norton). Follow him on X @SquigglyVolcano

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Highly Invasive Spotted Lanternflies May Have a Surprising Weakness: Vibrations

Spotted lanternflies are sometimes drawn to power line vibrations—and scientists are taking notice

By Claire Marie Porter


Cwieders/Getty Images

Ever since the seemingly indestructible spotted lanternfly began to infiltrate the U.S. East Coast in 2014, the hunt has been on for a way to stop it. The bug has devastated trees, grapevines, and other fruit crops, earning it a listing of potentially the most destructive invasive insect in 150 years by Pennsylvania State University. Its excrement, called "honeydew" by entomologists, feeds sooty mold and draws stinging insects. Managing the pest has proved difficult; it has no natural predator, and thus far there is no foreseeable end to its plaguing swarms.

USDA researchers have now found that lanternflies have an affinity for certain vibrations, they report in the *Journal of Economic Entomology*. "There was an anecdotal rumor that they were gathering near power lines," says study co-author Richard Mankin, an entomologist with the USDA Agricultural Research Service. For the new study, the team members wanted to see whether vibrations influence the bugs' movements on a surface. They found that in a laboratory setup, the bugs detected and moved toward 60-hertz vibrations (the common buzzlike frequency of power lines) generated with a speaker, says Miriam Cooperband, an entomologist with the USDA's Animal and Plant Health Inspection Service, who designed the study.

This reaction suggested the creatures might communicate using surface-transmitted vibrations, so Cooperband and her colleagues are now examining the vibrations the lanternflies produce. Understanding such communication signals may be key to setting an effective trap, Cooperband says. Beyond frequencies that attract the lanternflies, "there might be other types of signals that, when applied a certain way, might jam their communication and disrupt mating or even drive them away," she says.

Many attempts have been made to vanquish the spotted lanternfly, but its behavior differs from that of other pests that entomologists are used to managing, Mankin says. For example, lanternfly females and nymphs gather in massive swarms, called aggregations, that are not clearly tied to mating—so the typical pest-control method of disrupting reproduction is difficult to apply.

“The lanternfly is a freak bug, and there’s a long way to go to unlock all its secrets,” says Brian Walsh, a horticulture educator at Penn State who has also been investigating how to effectively manage the pest. He says that although this new research is interesting, it needs more refinement before it might produce a broadly usable pest-management approach. “I hope that it does work out and that a scalable tool can be developed as a lure for the spotted lanternfly that produces more than a hyperlocalized impact,” he says. “That would be a massive game changer in our management efforts, as none currently exist.”

Claire Marie Porter is a Pennsylvania-based freelance journalist who writes about health and environmental sciences. Her recent work appears in Undark Magazine and the *Atlantic*.

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How Baby Orangutans Become Master Treehouse Architects

Most orangutans take seven years to learn to make their own beds

By Sierra Bouchér

An orangutan and her daughter in their day nest.
Anup Shah/Getty Images

Orangutans are known for an impressive feat of engineering: They carefully weave an intricate nest from branches and leafy twigs in the forest canopy daily, building and rebuilding for cozy nights and shady midday naps. Some nests, particularly those made by older and more experienced orangutans, feature pillows, linings, blankets, and sometimes even a roof fashioned from broad leaves—and all must be well protected from the elements and strong enough to hold 100-plus pounds of slumbering ape.

Now a study published in *Animal Behaviour* reveals that young orangutans perfect this vital task over the course of seven years. “The fact that it takes them so long to acquire this skill shows us that it’s much more complex than we realized before,” says the study’s lead author Andrea Permana, a primatologist at the University of Warwick in England.

To understand this behavior, researchers followed 45 orangutans at Indonesia’s Gunung Leuser National Park for 13 years. “It was very cool to see more focus on material culture and tool-use behavior that isn’t the standard ‘sticks and stones,’ like the caveman tools that we usually focus on,” says University of Kent primatologist Hella Péter, who was not involved in the study.

Permana found that orangutans begin to show interest in nest building as young as six months. These still dependent orangutans practice the task daily over the course of their youth, watching their mother to learn building techniques. As they get older, their strength and dexterity improve, letting them more successfully manipulate twigs and branches into the structure. Researchers have seen orangutans build their first functional night nests at three years old, but they still tend to sleep alongside their mothers until about age seven.

Orangutans “have this seven- to nine-year-long dependency period where they are little babies, and after that they are on their own,” Péter says.

These nests offer more than just cover from tigers and other predators; sleep itself is a crucial resource as well. All great apes construct nests to some degree, and studies show that orangutans sleep deeper and longer than non-nest-building primates. This sound sleep may tell us how nests played a part in our own ancestors’ brain evolution because human ancestors and orangutan ancestors developed nest building simultaneously, Permana says: “The more rested you are, then you can be more innovative. Maybe you’re more curious, your memory is better, and you can solve problems better. The knock-on effects of that on the success of our ancestors is pretty undoubtable.”

Sierra Bouchér is a freelance journalist who covers intersections of people and nature.

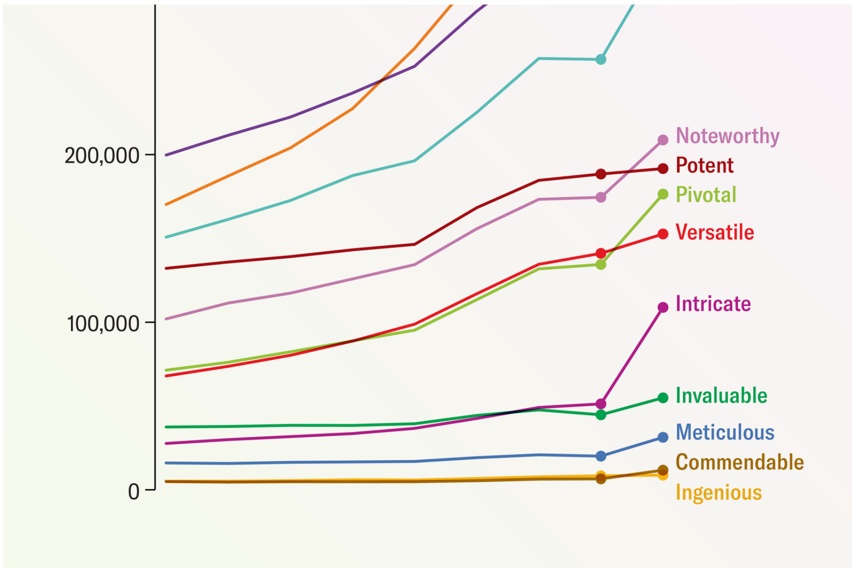
Artificial Intelligence

- **Chatbots Have Thoroughly Infiltrated Scientific Publishing**
  One percent of scientific articles published in 2023 showed signs of generative AI's potential involvement, according to a recent analysis

AI Chatbots Have Thoroughly Infiltrated Scientific Publishing

One percent of scientific articles published in 2023 showed signs of generative AI's potential involvement, according to a recent analysis

By Chris Stokel-Walker



Amanda Montañez; Source: Andrew Gray

Researchers are misusing ChatGPT and other artificial intelligence chatbots to produce scientific literature. At least, that's a new fear that some scientists have raised, citing a stark rise in suspicious AI shibboleths showing up in published papers.

Some of these tells—such as the inadvertent inclusion of "certainly, here is a possible introduction for your topic" in a recent paper in *Surfaces and Interfaces*, a journal published by Elsevier—are reasonably obvious evidence that a scientist used an AI chatbot known as a large language model (LLM). But "that's probably only the tip of the iceberg," says scientific integrity consultant Elisabeth Bik. (A representative of Elsevier told *Scientific American* that the publisher regrets the situation and is investigating how it could have “slipped through” the manuscript evaluation process.) In most other cases AI involvement isn’t as clear-cut, and automated AI text detectors are unreliable tools for analyzing a paper.

Researchers from several fields have, however, identified a few key words and phrases (such as “complex and multifaceted”) that tend to appear more often in AI-generated sentences than in typical human writing. “When you’ve looked at this stuff long enough, you get a feel for the style,” says Andrew Gray, a librarian and researcher at University College London.

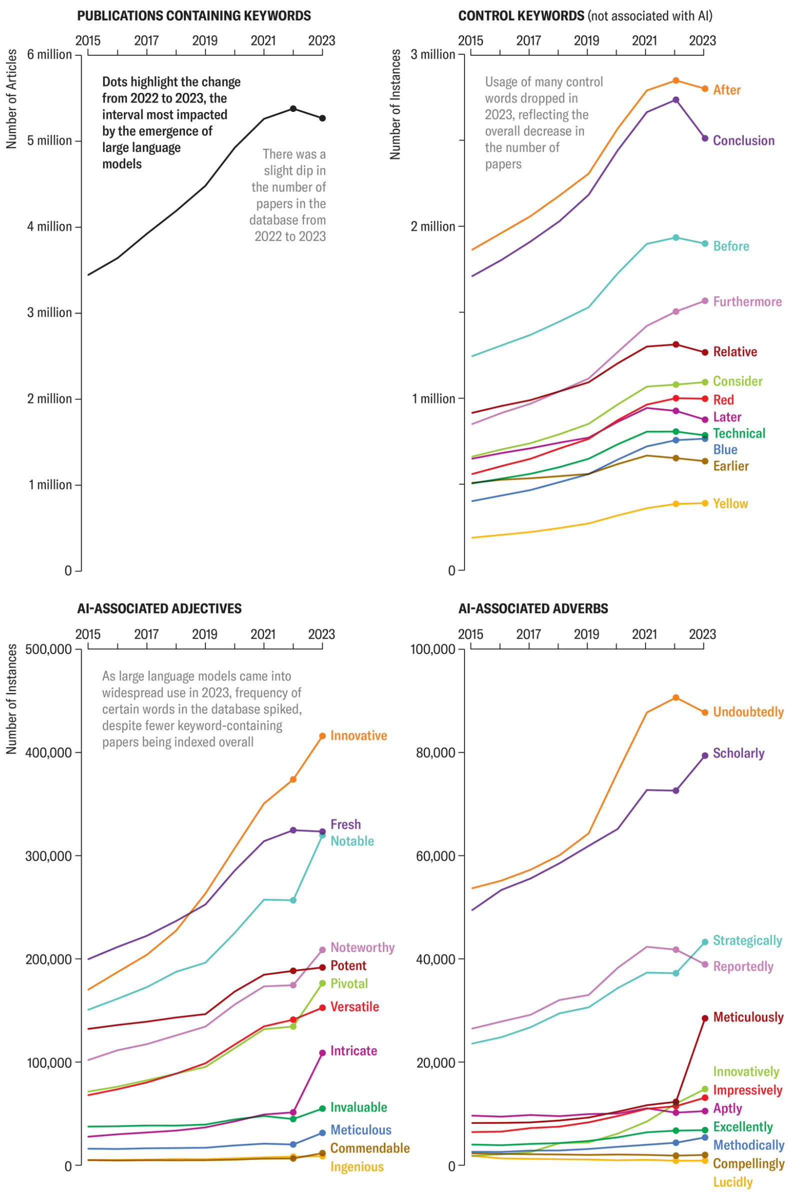
LLMs are designed to generate text—but what they produce may or may not be factually accurate. “The problem is that these tools are not good enough yet to trust,” Bik says. They succumb to what computer scientists call hallucination: simply put, they make stuff up. “Specifically, for scientific papers,” Bik notes, an AI “will generate citation references that don’t exist.” So if scientists place too much confidence in LLMs, study authors risk inserting AI-fabricated flaws into their work, mixing more potential for error into the already messy reality of scientific publishing.

Gray recently hunted for AI buzzwords in scientific papers using Dimensions, a data analytics platform that its developers say tracks more than 140 million papers worldwide. He searched for words disproportionately used by chatbots, such as “intricate,” “meticulous” and “commendable.” These indicator words, he says, give a better sense of the problem’s scale than any “giveaway” AI phrase a clumsy author might copy into a paper. At least 60,000 papers—slightly more than 1 percent of all scientific articles published globally last year—may have used an LLM, according to Gray’s analysis, which was released on the preprint server arXiv.org and has yet to be peer-reviewed. Other studies that focused specifically on subsections of science suggest even more reliance on LLMs. One such investigation found that up to 17.5 percent of recent computer science papers exhibit signs of AI writing.

Suspicious Trends in Word Usage

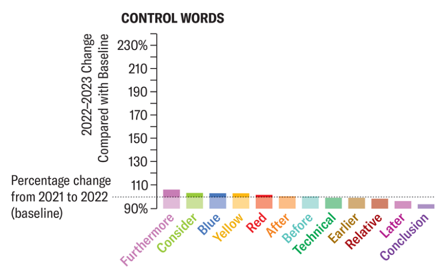
For each year, starting with 2015, librarian and researcher Andrew Gray used the Dimensions database to count the number of published scientific papers that contained certain keywords and the total number of times each keyword was used. He used a set of 12 neutral "control" words, along with 12 adjectives and 12 adverbs that are associated with large language models such as ChatGPT.

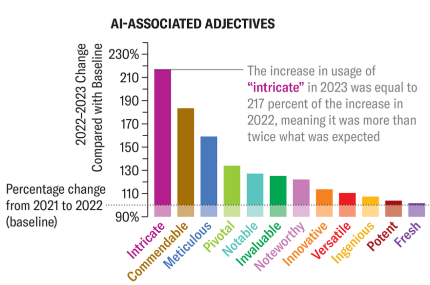
Changes in Publishing Volume and Word Usage over Time

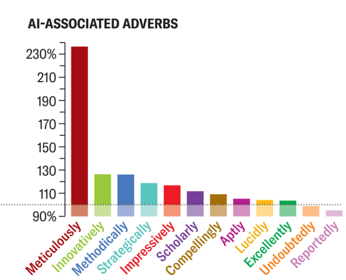


Anomalies in Year-over-Year Changes

Gray adjusted the annual frequency of each word to account for the number of keyword-containing papers included in the database for that year. Then he compared each year-over-year increase or decrease with the previous one. By this metric, control words saw little varation in 2023, whereas some AI-associated ones far exceeded expectations.







Amanda Montañez; Source: Andrew Gray

Those findings are supported by *Scientific American*'s own search using Dimensions and several other scientific publication databases, including Google Scholar, Scopus, PubMed, OpenAlex and Internet Archive Scholar. This search looked for signs that can suggest an LLM was involved in the production of text for academic papers—measured by the prevalence of phrases that ChatGPT and other AI models typically append, such as "as of my last knowledge update." In 2020 that phrase appeared only once in results tracked by four of the major paper analytics platforms used in the investigation. But it appeared 136 times in 2022. There were some limitations to this approach, though: It could not filter out papers that might have represented studies of AI models themselves rather than AI-generated content. And these databases include material beyond peer-reviewed articles in scientific journals.

Like Gray's approach, this search also turned up subtler traces that may have pointed toward an LLM: it looked at the number of times stock phrases or words preferred by ChatGPT were found in the scientific literature and tracked whether their prevalence was notably different in the years just before the November 2022 release of OpenAI's chatbot (going back to 2020). The findings suggest something has changed in the lexicon of scientific writing—a development that might be caused by the writing tics of increasingly present chatbots. "There's some evidence of some words changing steadily over time" as language normally evolves, Gray says. "But there's this question of how much of this is long-term natural change of language and how much is something different."

Symptoms of ChatGPT

For signs that AI may be involved in paper production or editing, *Scientific American*'s search delved into the word "delve"—which, as some informal monitors of AI-made text have pointed out, has seen an unusual spike in use across academia. An analysis of its use across the 37 million or so citations and paper abstracts in life sciences and biomedicine contained within the PubMed catalog highlighted how much the word is in vogue. Up from 349 uses in 2020, “delve” appeared 2,847 times in 2023 and has already cropped up 2,630 times so far in 2024—a 654 percent increase. Similar but less pronounced increases were seen in the Scopus database, which covers a wider range of sciences, and in Dimensions data.

Other terms flagged by these monitors as AI-generated catchwords have seen similar rises, according to the *Scientific American* analysis: “commendable” appeared 240 times in papers tracked by Scopus and 10,977 times in papers tracked by Dimensions in 2020. Those numbers spiked to 829 (a 245 percent increase) and 20,536 (an 87 percent increase), respectively, in 2023. And in a perhaps ironic twist for would-be “meticulous” research, that word doubled on Scopus between 2020 and 2023.

More Than Mere Words

In a world where academics live by the mantra “publish or perish,” it’s unsurprising that some are using chatbots to save time or to bolster their command of English in a sector where it is often required for publication. But employing AI technology as a grammar or syntax helper could be a slippery slope to misapplying it in other parts of the scientific process. Writing a paper with an LLM co-author, the worry goes, may lead to key figures generated whole cloth by AI or to peer reviews that are outsourced to automated evaluators.

These are not purely hypothetical scenarios. AI certainly has been used to produce scientific diagrams and illustrations that have often been included in academic papers—including, notably, one bizarrely endowed rodent—and even to replace human participants in experiments. And the use of AI chatbots may have permeated the peer-review process itself, based on a preprint study of the language in feedback given to scientists who presented research at conferences on AI in 2023 and 2024. If AI-generated judgments creep into academic papers alongside AI text, that concerns experts, including Matt Hodgkinson, a council member of the Committee on Publication Ethics, a U.K.-based nonprofit organization that promotes ethical academic research practices. Chatbots are “not good at doing analysis,” he says, “and that’s where the real danger lies.”

A version of this article entitled “Chatbot Invasion” was adapted for inclusion in the July/August 2024 issue of Scientific American.

Chris Stokel-Walker is a freelance journalist in Newcastle, England.

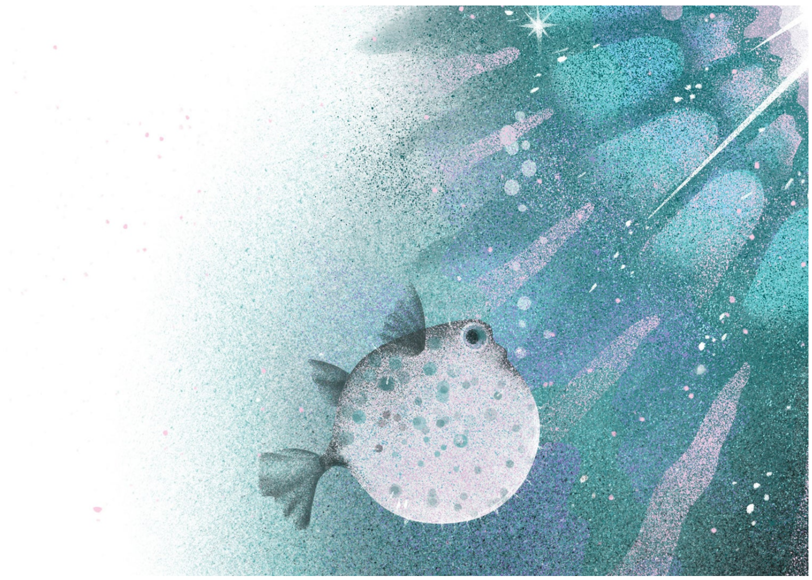
Arts

- **Poem: ‘An Ars Poetica’**
  Science in meter and verse

Poem: ‘An *Ars Poetica*’

Science in meter and verse

By Allison Funk


Masha Foya

Edited by Dava Sobel

It, too, will be swept away,
   but for now on the seabed
the humble Japanese pufferfish
   is creating something
grander than he is alone.

   Much as a Tibetan
artist taps his wand to release
   a fine stream of sand,
he brushes his fins along the ocean floor
   to shift the ancient grains,

On supporting science journalism

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stirring up enough dust
   for him to vanish
into its clouds, this creature
   that’s not much to look at anyway.
Seemingly unremarkable

   apart from his labor,
he toils for a week of days and nights
   to perfect a shape as symmetrical
as the rose window it resembles.
   If that weren’t enough,

before finishing,
   with the skill of someone
threading sequins on lace,
   he’ll adorn his tracery with seashells,
and swish, swish,

   is that a faint signature of fin prints
he’s left on his masterpiece?
   Few of us could fail to understand
his loneliness, his longing to be seen,
   if only by a she-fish

that comes and goes.
   Oh love, that imperfect art
that accompanies us in the depths.
   How dark it would be otherwise,
how cold this far under.

Allison Funk often touches on science themes in her six poetry collections, including *Wonder Rooms* (2015) and *The Visible Woman* (2021), both published by Parlor Press. “An *Ars Poetica*” will appear in a volume of her new and selected poems supported by a recent fellowship from the John Simon Guggenheim Memorial Foundation.

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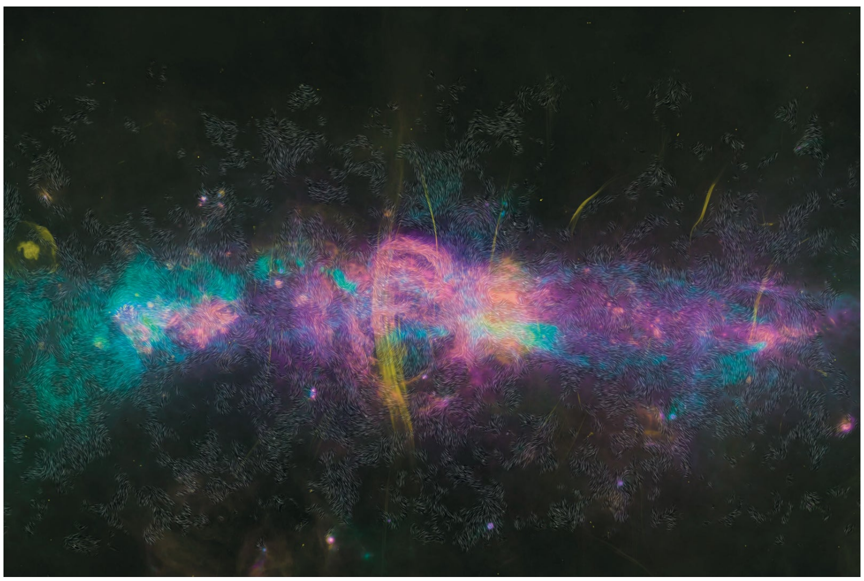
Astronomy

- **Dazzling New Milky Way Map Shows How Magnetism Shapes Our Galaxy**
  An image of interstellar dust moving through the Milky Way’s magnetic field may help scientists learn more about the origin of galaxies
- **Astronomers Are Snapping Baby Pictures of Planets by the Dozen**
  Snapshots of a plethora of planet-forming disks offer more than just eye candy—they also reveal some fundamental aspects of how worlds are born

Dazzling New Milky Way Map Shows How Magnetism Shapes Our Galaxy

An image of interstellar dust moving through the Milky Way’s magnetic field may help scientists learn more about the origin of galaxies

By Riis Williams



D. Paré, K. Karpovich and D. Chuss/Villanova University (PI); Three-color background image also uses data from European Space Agency (ESA), Herschel Space Observatory and South African Radio Astronomy Observatory (SARAO) and MeerKAT Radio Telescope

Our galaxy took shape more than 13 billion years ago, when clouds of cosmic dust collapsed from their own gravitational pull, and the resulting heat and pressure slowly transformed them into stars and planets ... or something like that. Details of the Milky Way’s origin story are still fuzzy, and studying this ancient process is exceptionally tricky.

But a new map of the galactic center and its magnetic field offers scientists an unprecedentedly detailed look into the forces that powered our galaxy’s emergence. Researchers around the world spent four years gathering and combining telescope data that show

how interstellar dust across 500 light-years of the Milky Way’s center interacts with the galaxy’s magnetic field.* The resulting map is the first to depict the field with such clarity at this resolution, says the project’s principal investigator, Villanova University physicist David T. Chuss.

Chuss and his team studied space dust using the Stratospheric Observatory for Infrared Astronomy, a NASA telescope that tracked infrared light while mounted in an aircraft flown at 45,000 feet. Magnetic fields cause light waves emitted by dust to orient in particular ways, giving that light a property called polarization—so measuring the polarization can reveal nearby magnetism. Villanova physicist Dylan Paré and his colleagues converted the telescope’s data into segments suitable for visual representation, and Kaitlyn Karpovich, then an undergraduate student, crafted the colorful background using additional telescopes’ data on dust temperature and dispersion.

The colors symbolize different particle temperatures: blue and purple indicate cold and warm dust, respectively, and yellow denotes hot gas. The small, swirling gray lines represent the magnetic field. “I’m still pretty astounded at how complex the field is,” Chuss says. “I stare at this map a lot but am still always noticing new things about it.”

Astronomer Roberta Paladini of the California Institute of Technology says studying Milky Way dust can illuminate the elaborate interplay between gravity and magnetism, helping scientists investigate when and why dust clouds collapse to form stars. “When we have these two forces working in balance, the cloud doesn’t collapse,” she says. “But at some point gravity always wins—and examining magnetic fields will help us know when collapse actually happens and stars emerge.”

**Editor’s Note (7/8/24): This sentence was edited after posting to correct the description of dust across 500 light-year’s of the galaxy’s center.*

Riis Williams is a New York City–based science journalist who specializes in climate, health and wildlife reporting. She formerly served as *Scientific American*’*s* news intern.

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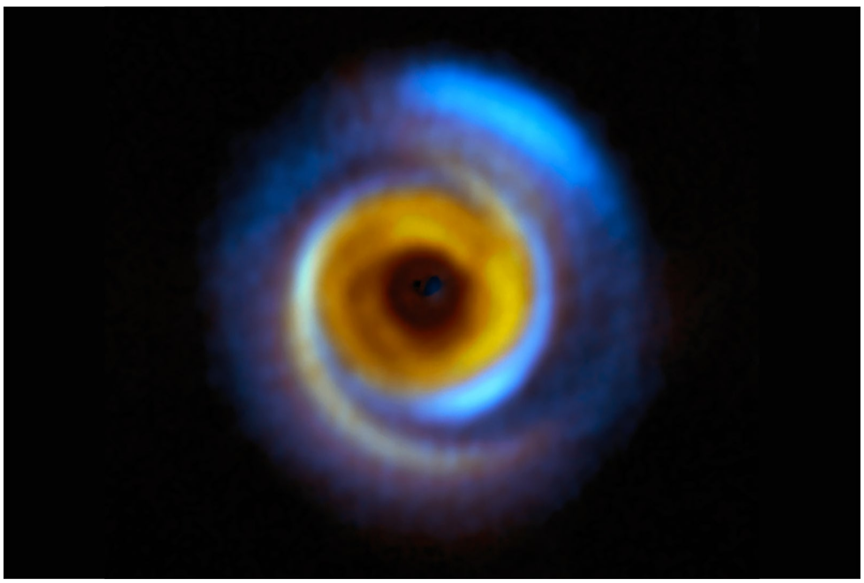
Astronomers Are Snapping Baby Pictures of Planets by the Dozen

Snapshots of a plethora of planet-forming disks offer more than just eye candy—they also reveal some fundamental aspects of how worlds are born

By Phil Plait



The MWC 758 planet-forming disk is about 500 light-years away.
ESO/A. Garufi et al.; R. Dong et al.; ALMA (ESO/NAOJ/NRAO) (CC BY 4.0)

For centuries—and, frankly, until quite recently—astronomers were baffled by planet formation. They saw points of light in the sky moving in a neat, orderly fashion, but many crucial details about how those worlds got there in the first place were a mystery.

We've come a long, long way since those times—and with remarkable speed. With the help of bigger telescopes, more precise instruments and advanced digital image-processing techniques, answering the question of how planets form has gone from speculative guesswork to a robust field of study. And, like most new scientific disciplines, it's evolving rapidly. We used to have just a few observations of embryonic planetary systems but now have hundreds thanks to the breathtaking pace of discovery.

In fact, astronomers recently delivered detailed observations of 86 nascent planetary families, adding a staggering number of objects for researchers to gleefully analyze. And with that analysis will come a better understanding of how stars and planets are born.

In Ye Olden Days—such as when I was a kid—the scientific understanding of planetary formation was weak, and a lot of the ideas that were tossed around could safely be called “wacky.” For example, one was that a star passed so close to our sun that it drew strands of material out of it, and those strands coalesced to form planets. This is a pretty cool idea—at least its proponents were “thinking big”—but it’s a stretch, to say the least. For one thing, such close near-collisions between stars in this part of the galaxy are so rare as to be virtually nonexistent. And that kind of superheated solar streamer would dissipate to nothingness, not collapse into tidy, enduring worlds.

But as time went on and the observations got better, so did the hypotheses. Now we know that stars form in gigantic clouds of gas called nebulae when overly dense clumps of material collapse under their own gravity. The material flattens into a protostellar disk, with matter swirling around the center and feeding the young star forming there. Eventually the disk—now called a protoplanetary disk—cools and can truly begin the planetary-formation process. Planets grow either as small objects, such as pebbles and rocks, stick together to make bigger ones or as huge chunks of the disk collapse to directly create large objects.

> The study of planetary birth is at an inflection point. In the past, these objects were found only rarely, but now observations are sweeping them up wholesale.

These disks were theorized for decades, but no one actually detected any until the 1980s, when observations of the bright star Vega revealed it to be surrounded by a ring of starlight-warmed dust. More were quickly found, although the observations were short on diagnostic detail.

That changed when a crew of astronauts installed the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope in 1997. STIS was able to block most of a target star's brilliant glare and deliver high-resolution images of any sizable circumstellar disk. Many of the disks discovered with STIS bore spiral arms—an indication of unseen planets that were setting the disks aswirl with their gravity. In others, scientists saw clear gaps in the disk where planets were either plowing through material and sweeping it up or pumping orbital energy into the particles there and changing their trajectory. (Full disclosure: I worked on STIS and was part of the project that looked at these disks. In that research, I helped to digitally remove the star's light. Being one of the first people to ever see these structures in detail was an honor and a joy.)

The study of these disks has, of course, moved on since then and, incredibly, has gotten even better. The Atacama Large Millimeter/submillimeter Array (ALMA) observatory in Chile has scrutinized dozens of such structures and revealed previously unseen details in wavelengths of light near the radio range. And now astronomers are bridging the gap between visible light and radio with the European Southern Observatory's immense Very Large Telescope (VLT), also in Chile. It's composed of four gigantic 8.2-meter telescopes, and on one of these beasts sits SPHERE, the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument. It's a phenomenally high-resolution camera that takes images with such exquisite detail that, no joke, when I first saw its astonishing pictures of asteroids in our solar system, I thought I was being pranked.

Each of the VLT's four telescopes is so big that it can collect a lot of light and see fine detail, so it's able to observe many stars in the throes of creation and discern structures in the surrounding material—features created by massive objects such as protoplanets forming in a disk. In three papers in the journal *Astronomy & Astrophysics*, astronomers report findings from their observations of planetary systems emerging in three nearby nebulae in the constellations of Orion, Taurus and Chamaeleon. Each of these star-forming factories is close enough to Earth that the powerful VLT-SPHERE combo reveals myriad details. Many of the observed disks have gaps and spiral arms, signaling the growth of planets and, more important, putting the disks in context with their immediate astrophysical surroundings.

For example, in the Taurus cloud, SPHERE observed roughly 20 percent of the nebula's Class II objects (those where the light from the newly born star is just emerging from the protostellar murk), representing a complete sample of all stars with more than 0.4 times the sun's mass—the rest were too faint to be reliably detected. Of these, nearly two thirds had faint disks that had been neither seen nor documented before.

Nearly a third of the systems observed in the Taurus cloud were multiple-star systems, in which two or more stars orbit one another. Statistics show that about half of all stars are—unlike our sun—in multiple systems, so studying planetary formation in these Tatooine-like environments will yield a lot of interesting data on how stellar multiplicity affects the planets around those stars. For example, in the Chamaeleon cloud studied by SPHERE, disks were sparse within binary systems where the higher-mass primary star was accompanied by a close-orbiting, lower-mass secondary star, which implies that some aspect of that stellar configuration suppresses the formation of planet-birthing disks.

Individual stars and disks are wonderful for learning about specific physical circumstances, but we need broader observations to get a better overview of how planets come into being—in a sense, we can understand the fine details only by seeing how they fit into the bigger picture. Comparing and contrasting the characteristics of these planetary nurseries, including their density, age and chemical structure, is what will lead to that gestalt.

The study of planetary birth is at an inflection point. In the past, these objects were found only rarely, but now observations are sweeping them up wholesale. As I like to say about new fields of science, this is when it goes from stamp collecting to zoology—from “We found another of these weird objects!” to “We have enough that we’re starting to note trends and see the underlying mechanisms that create them.”

There are still many questions about how our own solar system came to be and evolved over the eons into its current configuration. A critical step toward answering them is to make observations that let us find the deeper connections between other planetary systems and ours.

You might think astronomy is the study of everything over your head, but in fact it includes what’s under your feet, too.

Phil Plait is a professional astronomer and science communicator in Virginia. He writes the *Bad Astronomy Newsletter*. Follow him online.

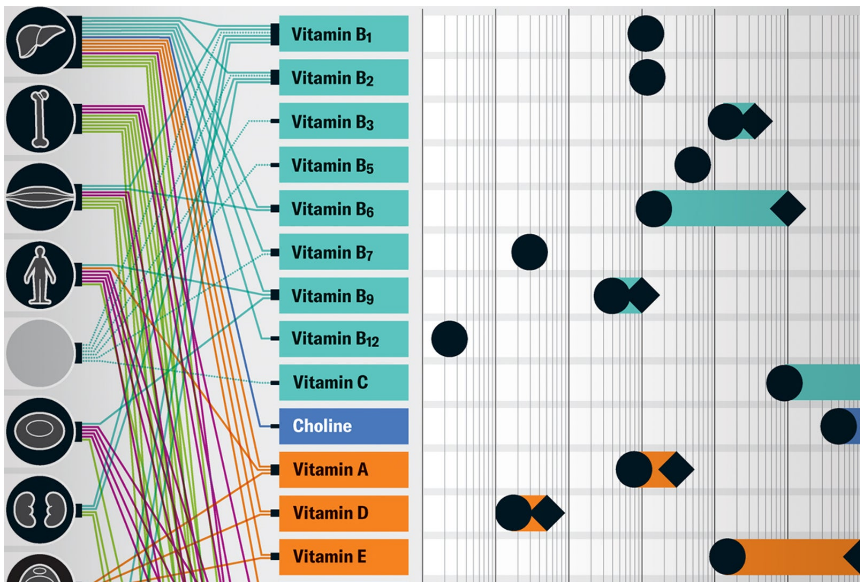
Basic Chemistry

- **What Vitamins and Minerals Really Do in Your Body**
  Humans need around 30 vitamins and minerals to keep our bodies functioning

What Vitamins and Minerals Really Do in Your Body

Humans need around 30 vitamins and minerals to keep our bodies functioning

By Clara Moskowitz, Jen Christiansen & Miriam Quick



Jen Christiansen

Food gives us energy, but just as important, it delivers vitamins and minerals. There is essentially no bodily function that doesn't depend on at least one of these compounds, roughly 30 of which are considered crucial. They help our hearts beat and our lungs breathe. They enable our bodies to build new muscle, skin and bone cells. They allow nerves to send signals to the brain and the immune system to fight invaders. We literally can't live without them.

The difference between vitamins and minerals is that the former are organic—made by a plant or animal—and the latter are not. We absorb vitamins directly from the plants and animals we eat. We get minerals, which come from rocks, dirt or water, sometimes from the environment and sometimes from living things we eat that absorbed them before they died.

“Vitamins and minerals work in wild and wondrous ways, some of which we understand, many of which we’re still trying to understand,” says Howard Sesso, associate director of the division of preventive medicine at Brigham and Women’s Hospital and medical editor of the *Making Sense of Vitamins and Minerals* report from Harvard Medical School. “And there’s tremendous variation in how we all consume, digest, absorb and utilize the nutrients in a particular food we’re eating.”

Key Functions • Listed here are the main known uses of different nutrients, although scientists suspect there are many that are undiscovered. Furthermore, vitamins and minerals often interact with one another and help to promote the reactions of other nutrients.

CATEGORY: Water-Soluble Vitamins

These vitamins can dissolve in water.

- **Vitamin B_1 (thiamin)** • Helps to turn food into energy. Promotes skin, hair, muscle and brain health. Critical for nerve function. • *Rich Food Sources: Pork, brown rice, soy milk, watermelon, acorn squash*

- **Vitamin B_2 (riboflavin)** • Helps to turn food into energy. Boosts skin, hair, blood and brain health. • *Rich Food Sources: Meat, milk, eggs, yogurt, cheese, green leafy vegetables*

- **Vitamin B_3 (niacin, nicotinic acid, nicotinamide)** • Helps to turn food into energy. Essential for healthy skin, blood cells, brain and nervous system. • *Rich Food Sources: Meat, poultry, fish, whole grains, mushrooms, potatoes, peanut butter*

- **Vitamin B_5 (pantothenic acid)** • Helps to turn food into energy. Helps to produce lipids, neurotransmitters, steroid hormones and hemoglobin. • *Rich Food Sources: Chicken, egg yolk, whole grains, broccoli, mushrooms, avocados*

- **Vitamin B_6 (pyridoxine, pyridoxal, pyridoxamine)** • Metabolizes amino acids and helps cells replicate. Helps to produce red blood cells and neurotransmitters essential for brain function. • *Rich Food Sources: Meat, fish, poultry, legumes, tofu, potatoes, bananas, watermelon*

- **Vitamin B_7 (biotin)** • Helps to convert food into energy and make glucose. Helps to build and break down some fatty acids. Promotes bone and hair health. • *Rich Food Sources: Whole grains, organ meats, egg yolks, soybeans, fish*

- **Vitamin B_9 (folate, folic acid, folacin)** • Metabolizes amino acids and helps cells multiply. Vital for new cell creation. Helps to prevent brain and spine birth defects when taken early in pregnancy. • *Rich Food Sources:* Asparagus, okra, spinach, turnip greens, broccoli, legumes, orange juice, tomato juice

- **Vitamin B_{12} (cobalamin, cyanocobalamin)** • Metabolizes amino acids and helps cells multiply. Protects nerves and encourages their growth. Helps to build red blood cells and

DNA. • *Rich Food Sources: Meat, poultry, fish, milk, cheese, eggs*

- **Vitamin C (L-ascorbic acid)** • Makes collagen, as well as the neurotransmitters serotonin and norepinephrine. Works as an antioxidant. Boosts the immune system. • *Rich Food Sources: Fruits (especially citrus), potatoes, broccoli, bell peppers, spinach, strawberries, tomatoes, brussels sprouts*

CATEGORY: Water-Soluble Nutrient

Choline is organic and water-soluble, but it's not classified as either a vitamin or a mineral. It's somewhat similar to B vitamins.

- **Choline (formerly called vitamin B_4)** • Helps to make the neurotransmitter acetylcholine. Aids in metabolizing and transporting fats. • *Rich Food Sources: Milk, eggs, liver, salmon, peanuts*

CATEGORY: Fat-Soluble Vitamin

These organic nutrients dissolve in fats and oils and are mostly found in fat tissue and the liver.

- **Vitamin A (retinoids—preformed vitamin A, beta carotene —converts to vitamin A)** • Important for vision, cell health, bone formation and immune system function. • *Rich Food Sources: Liver, fish, eggs, sweet potatoes, carrots, pumpkins, squash, spinach, mangoes, turnip greens*

- **Vitamin D (calciferol, cholecalciferol—vitamin D_3, ergocalciferol—vitamin D_2)** • Helps to keep calcium and phosphorus at normal levels in the blood. Assists in forming teeth and bones. • *Rich Food Sources: Fortified milk or* *margarine, fortified cereals, fatty fish (Your body also uses sunlight to make vitamin D.)*

- **Vitamin E (alpha-tocopherol)** • Acts as an antioxidant, aids the immune system and supports vascular health. • *Rich Food Sources: Vegetable oils, wheat germ, leafy green vegetables, whole grains, nuts*

- **Vitamin K (phylloquinone—vitamin K_1, menaquinones—vitamin K_2)** • Aids in bone formation. Activates proteins and calcium essential for blood clotting. • *Rich Food Sources: Cabbage, liver, eggs, milk, spinach, broccoli, sprouts, kale, collards, other green vegetables*

CATEGORY: Major Mineral

The body needs relatively large amounts of these minerals, although too much of one can sometimes block the absorption of another.

- **Calcium** • Helps to build and protect teeth and bones. Aids with muscle function, blood clotting, nerve impulse transmission, hormone secretion and enzyme activation. • *Rich Food Sources: Yogurt, cheese, milk, tofu, sardines, salmon, fortified juices, broccoli, kale*

- **Chloride** • Balances fluids in the body and forms part of the stomach acid, which helps to digest food. • *Rich Food Sources: Salt (sodium chloride), soy sauce, processed foods*

- **Magnesium** • Necessary for chemical reactions in the body. Aids in muscle contraction, blood clotting and regulation of blood pressure. Helps to build bones and teeth. • *Rich Food Sources: Spinach, broccoli, legumes, cashews, sunflower and other seeds, halibut, whole wheat bread, milk*

- **Phosphorus** • Builds and protects bones and teeth. Forms a part of DNA and RNA. Helps to convert food into energy. Helps to move nutrients into and out of cells. • *Rich Food Sources: Milk and dairy products, meat, fish, poultry, eggs, liver, green peas, broccoli, potatoes, almonds*

- **Potassium** • Helps to balance fluids in the body. Helps to maintain a steady heartbeat and send nerve impulses. Required for muscle contractions. • *Rich Food Sources: Meat, milk, fruits, vegetables, grains, legumes*

- **Sodium** • Helps to balance fluids in the body. Helps to send nerve impulses. Needed for muscle contractions. Impacts blood pressure. • *Rich Food Sources: Salt, soy sauce, processed foods, vegetables*

- **Sulfur** • Helps to shape and stabilize protein structures. Necessary for healthy hair, skin and nails. • *Rich Food Sources: Protein-rich foods, such as meat, fish, poultry, nuts, legumes*

CATEGORY: Trace Mineral

Only small quantities of these are necessary for the body, but they are as essential as the major minerals.

- **Chromium** • Boosts insulin activity, helps to maintain normal blood glucose levels, and is required to free energy from glucose. • *Rich Food Sources: Meat, poultry, fish, eggs, potatoes, some cereals, nuts, cheese, brewer's yeast*

- **Copper** • Important for iron metabolism and the immune system. Helps to make red blood cells. • *Rich Food Sources:* Liver, shellfish, nuts, seeds, whole-grain products, beans, prunes, cocoa, black pepper

- **Fluoride** • Strengthens bones and stimulates new bone formation. Prevents tooth decay. • *Rich Food Sources: Fluoridated water, toothpaste with fluoride, marine fish, teas*

- **Iodine** • Necessary for synthesizing thyroid hormones, which help to maintain body temperature and influence nerve and muscle function. • *Rich Food Sources: Iodized salt, processed foods, seafood*

- **Iron** • Helps to transport oxygen through the body. Required for chemical reactions in the body and for making amino acids, collagen, neurotransmitters and hormones. • *Rich Food Sources: Red meat, poultry, eggs, fruits, green vegetables, fortified bread and grain products*

- **Manganese** • Helps to form bones and metabolize amino acids, cholesterol and carbohydrates. • *Rich Food Sources: Fish, nuts, legumes, whole grains, tea*

- **Molybdenum** • Forms part of several enzymes, including one that protects against potentially deadly neurological damage in infants. • *Rich Food Sources: Legumes, nuts, grain products, milk*

- **Selenium** • Acts as an antioxidant and helps to regulate thyroid hormone activity. • *Rich Food Sources: Organ meats, seafood, walnuts, sometimes plants (depends on soil content), grain products*

- **Zinc** • Helps to form enzymes and proteins and to build new cells. Frees vitamin A from storage in the liver. Vital for the immune system, taste, smell and wound healing. • *Rich Food Sources: Red meat, poultry, oysters and some other seafood, fortified cereals, beans, nuts*

Delicate Balance

When we eat too much of one vitamin or mineral, it can cause the loss of another. For instance, an excess of sodium will deplete calcium because these nutrients bind together, causing the body to excrete them both when it flushes out the sodium.

Getting Enough

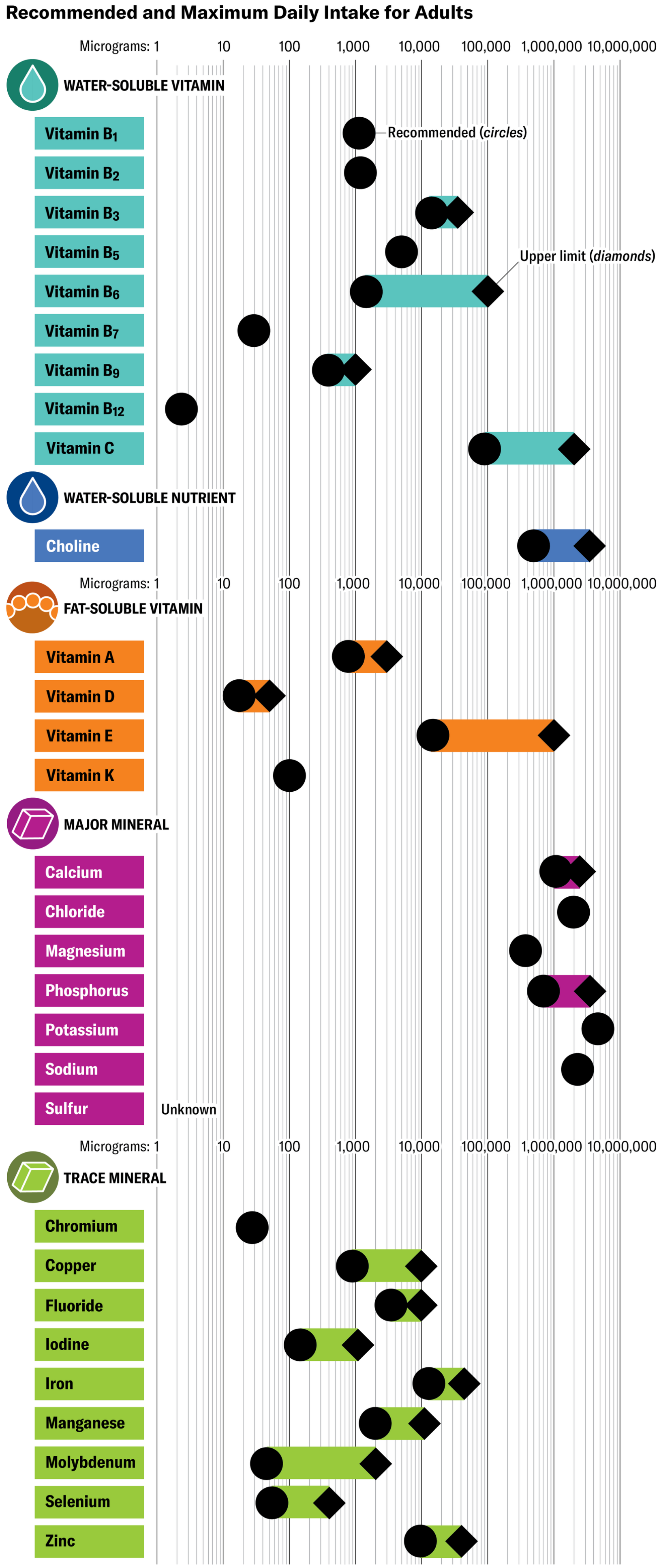
In the U.S., nutrition deficiencies are relatively rare, although malnutrition is increasing, especially among older age groups. The most common deficiencies are of vitamin B_6, iron and vitamin D. Of all the vitamins and minerals, Americans are least likely to be deficient in vitamin A, vitamin E and folate (B_9).

Beneficial combinations

Some nutrients work best as a team. Vitamin D helps us absorb calcium, for instance, and potassium encourages the excretion of excess sodium. Folate (B_9) is best absorbed if B_{12} is around, and the two work together to help cells divide and multiply.

Doses

The recommended daily intake depends on age, sex, and many other factors. Dosage icons here are purposefully large to show the big-picture variation between different nutrients.


Recommended and Maximum Daily Intake for Adults
Micrograms: 1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
WATER-SOLUBLE VITAMIN
Vitamin B_1
Vitamin B_2
Vitamin B_3
Vitamin B_5
Vitamin B_6
Vitamin B_7
Vitamin B_9
Vitamin B_{12}
Vitamin C
Recommended (*circles*)
Upper limit (*diamonds*)
WATER-SOLUBLE NUTRIENT
Choline
FAT-SOLUBLE VITAMIN
Vitamin A
Vitamin D
Vitamin E
Vitamin K
MAJOR MINERAL
Calcium
Chloride
Magnesium
Phosphorus
Potassium
Sodium
Sulfur
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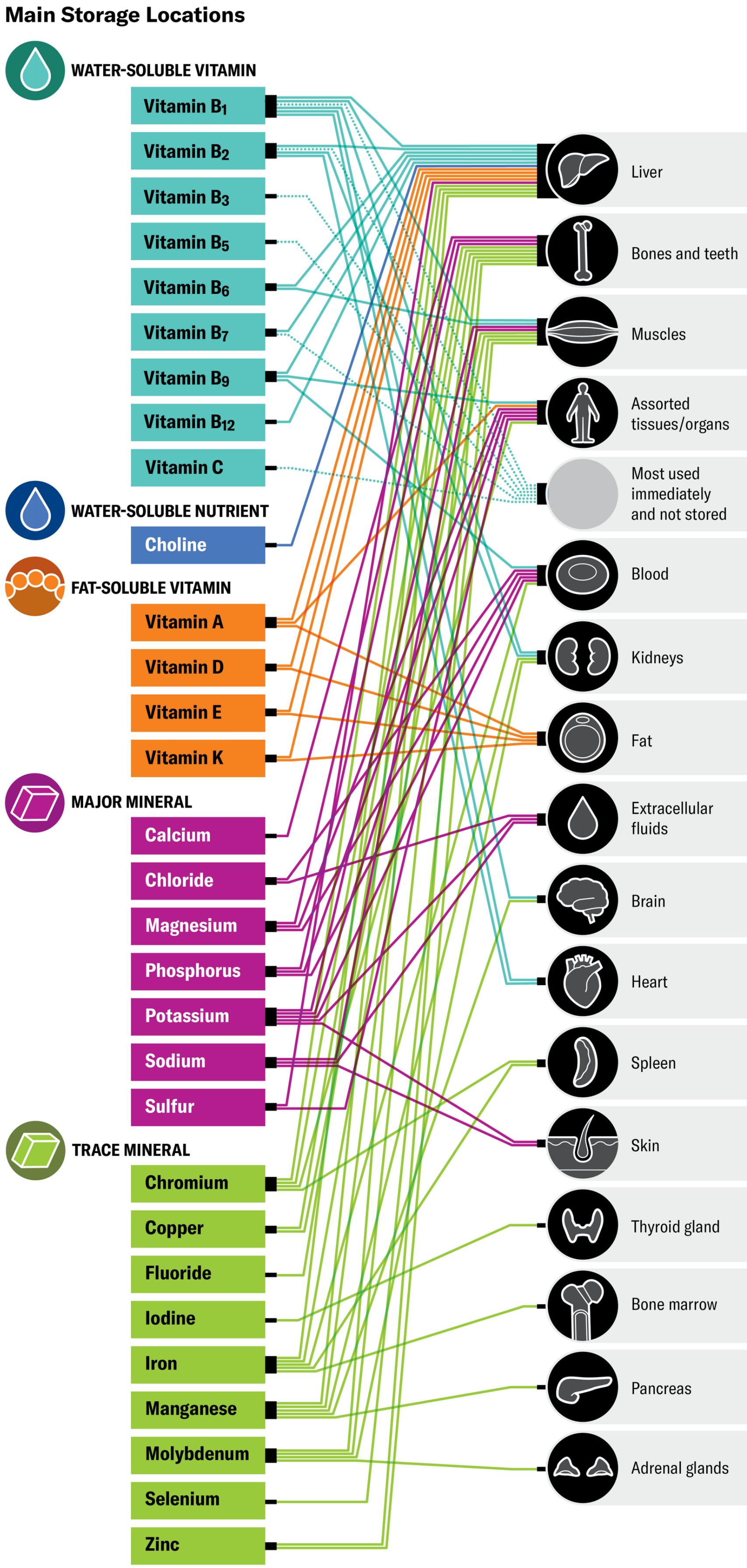
TRACE MINERAL
Chromium
Copper
Fluoride
Iodine
Iron
Manganese
Molybdenum
Selenium
Zinc

Jen Christiansen



Jen Christiansen

For more information: Dietary Supplement Fact Sheets, National Institutes of Health; Making Sense of Vitamins and Minerals, *a special health report by the editors at Harvard Health Publishing in consultation with Howard D. Sesso, 2022.*

Clara Moskowitz is a senior editor at *Scientific American*, where she covers astronomy, space, physics and mathematics. She has been at *Scientific American* for a decade; previously she worked at Space.com. Moskowitz has reported live from rocket launches, space shuttle liftoffs and landings, suborbital spaceflight training, mountaintop observatories, and more. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science communication from the University of California, Santa Cruz.

Jen Christiansen is author of the book *Building Science Graphics: An Illustrated Guide to Communicating Science through Diagrams and Visualizations* (CRC Press) and senior graphics editor at *Scientific American*, where she art directs and produces illustrated explanatory diagrams and data visualizations. In 1996 she began her publishing career in New York City at *Scientific American*. Subsequently she moved to Washington, D.C., to join the staff of *National Geographic* (first as an assistant art director–researcher hybrid and then as a designer), spent four years as a freelance science communicator and returned to *Scientific American* in 2007. Christiansen presents and writes on topics ranging from reconciling her love for art and science to her quest to learn more about the pulsar chart on the cover of Joy Division's album *Unknown Pleasures*. She holds a graduate certificate in science communication from the University of California, Santa Cruz, and a B.A. in geology and studio art from Smith College. Follow Christiansen on Bluesky @christiansenjen.bsky.social

Miriam Quick is a data journalist and researcher specializing in information visualization.

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Book Reviews

- ## Book Review: Why People Collect Trees and You Should, Too
  A new book about tree collectors shows how arboreal curation is an outlet for art and activism
- ## July/August 2024: Three New Books, Reviewed
  A riveting quest to map the world; quantum physics in a four-act drama; climate solutions that show what we’re doing right
- ## Book Review: Are The Wild Animals in Your Backyard a Nuisance or Neighbors?
  Call off the pest control and learn to live with wildlife

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Book Review: Why People Collect Trees and You Should, Too

A new book about tree collectors shows how arboreal curation is an outlet for art and activism

By Kathleen Yale


Schon/Getty Images

NONFICTION

The Tree Collectors: Tales of Arboreal Obsession
by Amy Stewart.
Random House, 2024 ($32)

“Growing fruit trees is a very simple way to stay in love with our world,” says Vivian Keh, playwright and daughter of immigrants, holding a basket of persimmons she’s cultivated to feel connected to her Korean ancestors. Keh is just one of 50 remarkable subjects in naturalist writer Amy Stewart’s *The Tree Collectors: Tales of Arboreal Obsession*, a compilation of portraits of people transformed by their love of trees.

On supporting science journalism

Initially, trees struck Stewart as an odd thing to collect—trees being, for the most part, large and difficult to sell or tuck into a suitcase the way philatelists might their beloved stamps and brandophilestheir cigar bands. Intrigued by this community of enthusiasts, she discovered educators, preservationists and visionaries, all hooked on a kind of curation, motivated by reasons as diverse as their projects. They plant trees in public and private spaces both modest and expansive, nurturing their collections to honor beloved dead, attract wildlife, preserve rare species, connect to history, invest in the future, grow food and create beauty. “When you ask people to tell you about the one activity they do not for money, not out of necessity, but to indulge their deepest passions and their wildest curiosities,” Stewart writes, “well, you’re in for an intimate conversation.”

Like all collectors, her subjects express a zeal for aesthetics, preservation, curiosity and delight. But it seems they know something else, too, something echoed by the recent rise in popularity of *shinrin-yoku*, or forest bathing, the Japanese practice of spending time in the woods: being around trees simply feels good.

Stewart captures this sensation by categorizing people according to their sense of purpose. Kenneth Høegh, one of the book’s “ecologists,” tests which cold-loving species might grow in a warming and historically treeless Greenland. “Healer” Joe Hamilton plants loblolly pines on a parcel of land he inherited from his enslaved ancestors, with an eye toward long-term sustainable forestry he hopes will establish a source of generational wealth for his family. Reagan Wytsalucy has a plan to restore traditional peach orchards on Navajo land as one of the “community builders” who seek to bring people together. The “artists” forge a creative practice through tree work. “I feel like our lives are all so piecemeal and hybridized and patched together,” says Sam Van Aken, who grafted 40 different stone fruits onto a single, dazzling cornucopia tree.

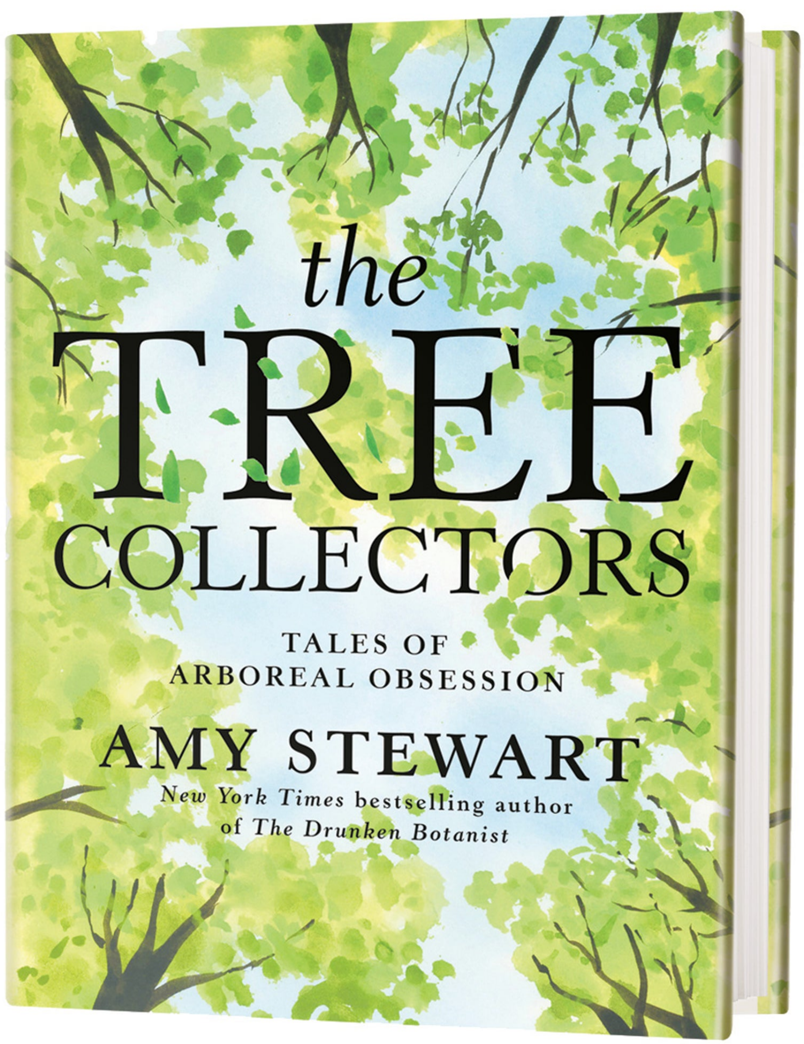
Not everyone curates actual trees. Some amass leaves or seeds or even images, such as Jianming Shen, who photographs ancient ginkgoes of particular significance in eastern China. When Dennis Wilson, a hobbyist woodworker, realized he couldn’t tell the difference between types of wood, he started a collection of small reference samples that is now nearly 7,000 samples deep. Forest ecologist Renee Galeano-Popp thought a road trip to look for diverse wild pine cones sounded like a fun way to spend her early retirement.

Adding to the book’s charm are Stewart’s watercolor illustrations—she gives us a look at each of her human subjects while also cataloging the most wondrous qualities of featured trees, such as Seussian eucalyptus seed pods and delicate camellia blossoms.

Some of the same stylistic elements that made Stewart’s best-selling previous books—*Wicked Plants* and *The Drunken Botanist*—such delightful compendiums are present here, too. There are glossaries of botanical terms and collective nouns for trees (the next time you’re in a birch grove, drop “betuletum” and impress your friends!). There are directories on where to visit moon trees (look for the Douglas fir in Olympia, Wash.). If you thrilled at Stewart’s gentle yet comprehensive guidance on making vermouths with foraged herbs, you’ll appreciate her practical tips on how to press leaves, graft branches, and plant tiny unauthorized forests on highway-median strips.

As a rule, Stewart's books emphasize that you need not own land, reside in the deep woods or trek to remote wilderness locations to deepen your relationship with nature; indeed, many of the most compelling stories in *The Tree Collectors* are based in urban spaces, backyards, and other surprising places.

After spending time in this varied commonwealth, you'll undoubtedly experience an intense desire to recline under the shade of a leafy canopy. But something even more profound is happening here: by creating a space for people to talk about something they love, Stewart made me feel more tender-hearted toward my fellow humans. "How often do any of us get a chance to pour our hearts out to a stranger?" she writes. "Somehow, talking about trees made it possible."



Kathleen Yale is an editor at *Orion* magazine and author of the award-winning children's book *Howl Like a Wolf!* (Storey, 2018). She lives in Montana.

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July/August 2024: Three New Books, Reviewed

A riveting quest to map the world; quantum physics in a four-act drama; climate solutions that show what we're doing right

By Dana Dunham, Maddie Bender & Amy Brady

IN BRIEF

Quantum Drama: From the Bohr-Einstein Debate to the Riddle of Entanglement

by Jim Baggott and John L. Heilbron.
Oxford University Press, 2024 ($32.99)

This meticulous account of the tumultuous evolution of quantum physics spans more than a century, including Albert Einstein and Niels Bohr's initial standoff at the fifth Solvay conference, in 1927, and recent work on the uncharted modern frontiers of quantum mechanics. Science writer Jim Baggott and professor of history John L. Heilbron balance depth and sophistication with sportscasterlike enthusiasm as they recount how the debate—wisely divided here into four acts—expanded to accommodate "the human passions and social contexts in which the ideas were conceived, debated, refined, accepted or rejected." The stakes of these theoretical wins and losses are as profound as our understanding of the purpose of science itself. —*Dana Dunham*

On supporting science journalism

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What If We Get It Right? Visions of Climate Futures
by Ayana Elizabeth Johnson.
One World, 2024 ($34)

“Peril and possibility coexist,” writes marine biologist (and *Scientific American* advisory board member) Ayana Elizabeth Johnson to explain this collection of essays and 20 interviews with climate visionaries. Despite an optimistic bent and eager embrace of solutions, including the founding of land trusts and investment in climate funds, these conversations are as much about “getting it right” as they are about what we are currently getting wrong. Johnson is a top-notch interviewer, and her guests are insightful and candid on topics ranging from community farming to environment-focused litigation. But written text often feels like the wrong format for these conversations—I would recommend the audiobook instead. —*Maddie Bender*

This Earthly Globe: A Venetian Geographer and the Quest to Map the World
by Andrea di Robilant.
Knopf, 2024 ($30)

Italian journalist Andrea di Robilant illuminates the geopolitical machinations and heart-pounding voyages of 17th-century explorers who would change how Europeans understood the shape of the world. Di Robilant animates the creation of a world map by recounting the swashbuckling adventures of Marco Polo, al-Hasan ibn Muhammad al-Wazzan, Father Francisco Álvares, and others. We glimpse the tireless work of Venice-based Giovambattista Ramusio, the humanist and editor who translated the explorers' documents while navigating the "growing climate of intolerance" toward secular writing ushered in by the Counter-Reformation. Scrupulously researched, This Earthly Globe reveals the riveting foundations of modern geography and cartography. —*Amy Brady*

Dana Dunham is a writer and editor based in Chicago.

Maddie Bender is a science writer and a producer at Hawaii Public Radio. She was a 2021 AAAS Mass Media Fellow at *Scientific American.*

Amy Brady is executive director of *Orion* magazine and a contributing editor at *Scientific American*. She is author of *Ice: From Mixed Drinks to Skating Rinks—A Cool History of a Hot Commodity* (G. P. Putnam's Sons, 2023).

Book Review: Are The Wild Animals in Your Backyard a Nuisance or Neighbors?

Call off the pest control and learn to live with wildlife

By Tove Danovich

A fox pauses in a backyard that is also now a home.
wessex photography/Getty Images

NONFICTION

Meet the Neighbors: Animal Minds and Life in a More-Than-Human World
by Brandon Keim.
W. W. Norton, 2024 ($29.99)

Anyone who follows stories of animal intelligence will have heard of exceptional animals. Snowball the cockatoo dances rhythmically to pop songs. Alex the parrot knew more than 100 words. Koko the gorilla might have had the language ability of a young child. But do animals need to be geniuses to be worthy of our attention?

Journalist Brandon Keim’s *Meet the Neighbors* is about ordinary animals—the bumblebees, coyotes, sparrows, raccoons and squirrels that live among us—and what it would take for people to be more considerate of the wild creatures who share our cities and backyards. Keim asks, “How might an awareness of animal minds shape the ways we understand them and, ultimately, how we live with them on this shared, precious planet?”

I was hooked from the opening pages, which detail a woman’s relationship with a bumblebee that she saves and nurses back to health. Keim’s enthusiasm for animals and the people who care about them is infectious. He interviews people who, for instance, spend hours cataloging the movements of local coyotes to prove they aren’t dangerous or overrunning the city and talks to scientists in Seattle who banded sparrows to watch how they socialized over the course of a year. In this thoughtful book, people’s experiences with animals and scientific studies about animal behavior become a springboard for asking bigger questions about how to treat animals more fairly.

In later chapters, Keim looks at various efforts to give animals legal standing so that their needs are represented alongside ours. What if we thought of the seasonal cycles of roosting swifts before taking down a chimney they've inhabited in the past? What if we considered animals as stakeholders that should be heard before harvesting timber from a forest, using pesticides in agriculture, or removing "nuisance" animals that aren't causing damage or harm?

It's now well documented that the so-called anthropause—the lack of human noise and activity that occurred during the COVID lockdown—made people more interested in the natural world around them. *Meet the Neighbors* asks how we'll use our newfound love to better coexist with nature—to be, in other words, better neighbors.

Tove Danovich is author of *Under the Henfluence: Inside the World of Backyard Chickens and the People Who Love Them (*Agate, 2023). She lives in Portland, Ore.

Conservation

- **Releasing Baby Cane Toads Teaches Predators to Avoid Toxic Adults**
  Australian conservationists introduced juvenile cane toads ahead of invasions to help prepare native monitor lizards

Releasing Baby Cane Toads Teaches Predators to Avoid Toxic Adults

Australian conservationists introduced juvenile cane toads ahead of invasions to help prepare native monitor lizards

By Gennaro Tomma

edelmar/Getty Images

After South American cane toads were introduced to Australia in the 1930s to control pestilent beetles, they ravaged the country's ecosystems—and their disruption continues today. These invasive amphibians secrete toxins from their skin, killing pets and other predators that eat them. The yellow-spotted monitor, a big lizard found mainly in Australia, has been especially hard-hit: populations have declined by more than 90 percent in most areas where cane toads invaded, with cascading effects on entire ecosystems. Now, to stem the problem, scientists are experimenting with a surprising way to dissuade the lizards from feasting on the toads.

Cane toads typically invade new areas as adults and then start reproducing. Wildlife management agencies and Indigenous groups track and predict the toads' progress across the continent based on their yearly movements and signs of their approach—such as dead animals they've poisoned. For a study in *Conservation Letters*, researchers tested what may at first seem like a counterintuitive idea: releasing cane toad eggs, tadpoles and youngsters in areas where monitors are present and adult toads are about to invade. Previous research had shown that monitors are only sickened—not killed—when they eat young cane toads, and the lizards thus have a chance to learn to avoid the more toxic adults in future encounters. “It's like we are rearranging the invasion dynamics,” says Georgia Ward-Fear, a conservation ecologist at Macquarie University in Sydney and lead author of the new study.

For the new work, the researchers first identified seven areas in Australia's tropical Kimberly region that would soon be overrun by cane toads. They then released a total of about 200,000 eggs, tadpoles and young cane toads across three of the seven sites during two years' wet seasons. The team used remote infrared and motion-detecting cameras to record the yellow-spotted monitor populations at each site before and after the adult cane toads eventually invaded.

The study found that monitor populations exposed to the young “teacher toads” often survived the adults' influx. In completely unexposed areas, however, the lizards virtually disappeared after the big toads showed up. “It's a management strategy that's now being adopted," Ward-Fear says, adding that Indigenous groups and wildlife management agencies have already begun using it based on the study's evidence.

"This research provides much hope in reducing the impacts of invasive species on native biodiversity," says Jodi Rowley, a conservation biologist at the Australian Museum in Sydney who wasn't involved in the study. She adds, however, that although this approach is "extremely exciting," each invasive species is likely to interact with its surroundings in different ways, and specific research is needed to find effective methods for protecting other animals and ecosystems.

Gennaro Tomma is a freelance science journalist. Follow him on X (formerly Twitter) @gennaro_tomma

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Culture

New Understandings of Food, Fat, Fitness and Evolution

Quantum observers, migrating mangroves, the deep history of an asteroid and understanding appetite in this issue of Scientific American

By Laura Helmuth

Scientific American, July/August 2024

There's never been a better time to eat. Those of us with the means and a decent grocery can buy fresh fruits and vegetables year-round. Dairy products are pasteurized and no longer teeming with dangerous microbes. The Dutch once waged war over nutmeg; now it's on aisle six.

We have the luxury of choice but also the burden of trying to make sense of all the conflicting messages about food and nutrition. Some of the most vigorous diet-advice nonsense comes from people who say we should eat like our ancestors did. But our ancestors didn't eat the way influencers claim. *Scientific*

American’s senior evolution editor Kate Wong explains what we evolved to eat (and ate to evolve), at the beginning of our special report on health and appetite.

A new class of drugs that mimic the hormone GLP-1 are helping people lose weight in part by changing how they think about food. *Scientific American* associate health editor Lauren J. Young covers newfound connections between the gut and brain. Obesity is now classified as a disease, but not everyone with obesity has symptoms of poor health, such as high blood pressure or insulin resistance. New research explores the unusual phenomenon of people who are heavy and healthy, and author Christie Aschwanden breaks down changing conceptions of weight and fat. Our Graphic Science column spells out what vitamins and minerals we need and how they act in the body.

A quantum particle exists in a “superposition” of states until someone observes it, at which point the metaphorical cat in the box either is or isn’t dead. Author Anil Ananthaswamy wrestles with one of the mind-bending questions of quantum theory: Who or what is the observer? An artificial intelligence might help resolve a long-standing paradox.

If any tree could walk, it would be a mangrove—just look at those leggy roots and branches. The trees are migrating north with climate change in the U.S., and Florida writer Michael Adno keeps up with the scientists who are tracking their new range in skiffs and on foot.

Cracks present a hazard to modern life—bridges, airplanes, condominiums and our own teeth can fail catastrophically when they fracture. Mathematician Manil Suri delves into the latest computer engineering research on the origins and growth of structural cracks and ways to prevent them.

Studies of meditation are entering a third wave, focused on advanced or deep meditation. Medical researchers Matthew D. Sacchet and Judson A. Brewer describe how they're studying these mental states in practitioners and what they can reveal about consciousness.

The OSIRIS-REx mission brought back bits of asteroid Bennu last year, and the first analyses of these samples show that Bennu was once part of a world that was wet, possibly tectonically active, and bathed in light from a star or stars that were destroyed before our own solar system existed. Isn't that wonderful? Science writer Robin George Andrews shares more here.

On July 16 we'll publish an online issue on "Fun and Games." Stop by our website for puzzles, playable games and interactives, as well as feature stories about new baseball rules, poker strategies, the Monty Hall problem and game history. We can help you choose a game that's right for you.

Recently we relaunched our podcast *Science Quickly* with a new host—writer and editor Rachel Feltman—and a new rhythm of news and deep dives. Please check it out.

Enjoy this supersize July/August issue and all our online offerings.

Laura Helmuth is editor in chief of *Scientific American*. She previously worked as an editor for the *Washington Post, National Geographic, Slate, Smithsonian* and *Science*. She is a former president of the National Association of Science Writers. She is currently a member of the National Academies of Sciences, Engineering, and Medicine's standing committee on advancing science communication and an advisory board member for SciLine and The Transmitter. She has a Ph.D. in cognitive neuroscience from the University of California, Berkeley. She recently won a Friend of Darwin Award from the National Center for Science Education. Follow her on Bluesky @laurahelmuth.bsky.social

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Contributors to *Scientific American*’s July/August 2024 Issue

Writers, artists, photographers and researchers share the stories behind the stories

By Allison Parshall

Peter Essick.
Peter Essick

Peter Essick
March of the Mangroves

In his career as a nature photographer, Peter Essick (*above*) has traveled to all 50 U.S. states, more than 100 countries and each of the seven continents. But while taking pictures for this issue’s feature story on mangroves’ migration into new habitats, by journalist Michael Adno, he remained closer to home. Essick, who lives near Atlanta, Ga., went to Florida’s Atlantic coast to accompany three experts as they pieced together the mystery of the northward-marching mangroves. “It’s like a little detective story,” he says. To capture the beauty of these swampy ecosystems, he donned rubber waders and wetsuits and piloted a drone.

Essick worked with *National Geographic* for 30 years, documenting both pristine natural beauty and ecosystems profoundly disrupted by humans. In his recently published photo book, *Work in Progress* (Fall Line Press), Essick documents the construction and urban development that are spreading out from Atlanta and threatening local ecosystems. “There’s nothing stopping it here in Atlanta in terms of a river or a mountain range,” he says; it’s going to “keep sprawling.”

Kate Wong
What Did Humans Evolve to Eat?

If you look for a diet to follow, you’ll encounter many scientific-sounding claims. A common one is that a particular diet is “what humans evolved to eat,” says Kate Wong, a senior editor at *Scientific American*, who has been covering archaeology and evolution for the magazine for more than two decades. “I wanted to ‘gut check’ that, if you will, against the fossil and archaeological record,” says Wong, whose feature in this issue’s special report takes on the question of what foods humans actually evolved to consume. “I’m not going to be telling you what to eat in this article. But what I can say is that humans evolved to be flexible eaters.”

Wong’s fascination with evolution and human origins goes way back. As a child, she went on a school trip to the American Museum of Natural History in New York City “and kind of fell in love with the place.” After studying biological anthropology in college, she briefly worked at the museum as a docent before getting a job at *Scientific American*, and the rest is history. She loves thinking about bygone worlds through fossils and artifacts. “I like looking at them and thinking about deep time and wondering what life was like back then,” Wong says. “This is all like catnip to me.”

Lauren J. Young
Turning Down the Food Noise

For the past couple of years Ozempic and similar drugs with weight-loss effects have been in the news constantly—and Lauren J. Young has been following the twists in the science as they occur. “So much of this research is happening basically in real time,” says Young, associate editor for health and medicine at *Scientific American*. Drugs like Ozempic mimic a hormone called glucagonlike peptide 1 (GLP-1) and have actions that go far beyond weight loss. “This hormone seems to affect so many aspects of the body”—including how our brains process hunger and cravings. For the special report in this month’s issue, Young set out to learn why.

Young grew up near Fresno, Calif., as the child of a pediatric dietitian and a food microbiologist. “Some of my best stories have come out of conversations with [my parents],” she says. Those include a project on Valley Fever, an understudied but potentially serious infection caused by a soil-dwelling fungus common in the U.S. Southwest. “The sheer number of people that story seems to have touched” is remarkable, Young says. “One of the most rewarding things about health journalism is that you really have direct impact for patients."

Ni-ka Ford
The Great Weight Debate

Ni-ka Ford has always known that she wanted to be an artist. But she wasn't sure how to channel that passion until her final year as a studio art major in college. She remembers one day in an art studio when she was looking out the window at a tree. "And I was like, 'Wow, the branches really look like veins in the body,'" she says. This inspiration led her to notice "a lot of similarities between our bodies and nature" and drew her to the field of medical illustration. Today her work distills medical complexity into illustrations and graphics that appear in journal articles, teaching materials and popular publications. For this issue's special report, Ford depicted both healthy and unhealthy adipose tissue in a feature on being heavy and healthy by journalist Christie Aschwanden.

Ford takes care to feature a range of body types and skin tones in her work. "I'm really passionate about bringing more diversity and representation into medical illustrations," which often feature exclusively white and slim bodies, she says. And as she creates her illustrations, she continues to take inspiration from nature, often picking her color palettes from photographs she has taken of sunsets. "What I found is that in nature, colors always look good together," Ford says. "I have made [this method] kind of a signature in my work."

Allison Parshall is an associate news editor at *Scientific American* who often covers biology, health, technology and physics. She edits the magazine's Contributors column and weekly online Science Quizzes. As a multimedia journalist, Parshall contributes to *Scientific American*'s podcast *Science Quickly*. Her work includes a three-part miniseries on music-making artificial intelligence. Her work has also appeared in *Quanta Magazine* and Inverse. Parshall graduated from New York University's Arthur L. Carter Journalism Institute with a master's degree in science, health and environmental reporting. She has a bachelor's degree in psychology from Georgetown University. Follow Parshall on X (formerly Twitter) @parshallison

Readers Respond to the March 2024 Issue

Letters to the editors for the March 2024 issue of Scientific American

By Aaron Shattuck

Scientific American, March 2024

SUN FACTS

"The Great Eclipse," Rebecca Boyle's informative article about April 8's total solar eclipse, describes materials of different temperatures in the sun's corona in the graphic "Portrait of Our Sun." Among them, it refers to "hot flaring plasma at or above 20 million K [kelvins]." The box text notes that the sun's core is 15 million K, and I wonder how that plasma can be about five million K hotter when the core is the main source of the sun's energy production.

ROBERT WALTY *STEPHENS CITY, VA.*

On supporting science journalism

Boyle says “a solar eclipse is one of the best ways for scientists to study the solar corona.” I thought satellite-based instruments were able to study the solar corona by masking out the sun’s disk. Are there Earth-based instruments that are not currently available on satellites?

DAVID LUNN *DEVON, ENGLAND*

BOYLE REPLIES: *In response to Walty: The sun’s core is the most consistently hot part of our star. But interactions among the sun’s magnetic field lines create intense bursts of energy in the solar corona, or outer atmosphere, called solar flares, and they can indeed reach temperatures of 20 million K or higher. The corona itself is about one million to two million degrees Celsius overall, and it’s hard to understand why it is so much hotter than the sun’s surface, which is only 6,000 degrees C. Magnetic activity is probably the source of the sun’s superheated atmosphere.*

To answer Lunn: A solar eclipse is the best way to study the sun’s atmosphere. Telescopes on Earth and satellites can use a coronagraph, an instrument that blocks the sun’s disk while leaving much of its atmosphere visible. But coronagraphs can block important parts of the solar atmosphere near the surface. In the atmosphere’s “transition region,” the area that is closest to the surface, it heats up dramatically, and the nature of the sun’s plasma changes. The region is key to understanding major solar phenomena such as the solar wind, not to mention clouds of charged particles called coronal mass ejections. (Although a *handful of spacecraft have been able to study the region, Earth-based observations during solar eclipses are very useful and in some ways more accessible.) What's more, most Earth-based coronagraphs are washed out by the daytime sky, which obscures many of the corona's features.*

An eclipse can also serve as a calibration tool, allowing us to compare data on the sun or background stars during the event with "regular" observations. Previous eclipses unveiled helium in the sun's atmosphere in 1868 and helped to demonstrate the gravitational bending of light predicted by Einstein's general theory of relativity in the early 20th century. During the April 2024 eclipse, NASA scientists measured the sun's radio waves as the moon slipped in front of it. By calculating the difference in radio signals, scientists hope to understand the strength of solar magnetic fields that produce them, which could provide insight into sunspots.

LASER SCOPE

A caption for the photograph in "The Era of Monster Telescopes," by Phil Plait [The Universe], mentions that the Extremely Large Telescope (ELT) in Chile will use lasers to create artificial stars. The article does not provide any more information about this. Are the lasers part of the calibration system or for some other use?

JONATHAN LAMB *CHARLESTON, S.C.*

PLAIT REPLIES: *The lasers are used to fine-tune the telescope's resolution. They emit a very specific color that's absorbed by sodium atoms in a thin layer in the atmosphere about 90 kilometers above Earth's surface. The atoms respond by glowing, creating a very small point of light—a bright artificial star. The ELT measures the changes in the spot as its light passes through our atmosphere and uses those data to rapidly deform a mirror that's in the light's* *path. The change in the mirror’s shape counteracts the “twinkling” of the star, focusing the telescope better and allowing it to see finer details in cosmic objects. This process is called adaptive optics and is pretty common now. It should enable the ELT to have incredibly sharp vision, even better than that of the Hubble Space Telescope.*

> “We must actively remove CO_2 from the air to keep the global average temperature below two degrees Celsius above the preindustrial average.”
> **—**Volker Sick *University of Michigan*

CARBON CAPTURE

In “The False Promise of Carbon Capture” [Observatory], Naomi Oreskes offers a valid criticism of what she refers to as “carbon capture” as it is typically practiced today. But humanity has a lot to lose if we give up on where the approach is headed.

Oreskes wisely underscores that most of the efforts being categorized as carbon capture right now are fueling rather than fighting climate change. The prevalence of the greenwashed practice of “enhanced oil recovery” is obscuring a technique that is essential to correcting our carbon trajectory in the short term and eventually ushering in a new circular carbon economy: carbon capture and utilization (CCU).

We’ve been using “carbon” as an abbreviation for “carbon dioxide.” But what utilization does is chemically convert that CO_2 to usable carbon, which is fundamental to products we rely on every day. Currently most of that carbon comes from fossil sources. To achieve net zero, we’re going to need to get it somewhere else, and biomass cannot meet global carbon demands. Direct air capture, while expensive right now, offers a solution for the long run. Utilization brings the net costs down: instead of being sequestered, the captured carbon becomes a feedstock to make valuable products such as fertilizer, aviation fuel, plastics and even concrete.

Although reducing carbon emissions and scaling up renewable energy must be priorities, they simply won't be enough on their own. We must actively remove CO_2 from the air to keep the global average temperature below two degrees Celsius above the preindustrial average. Carbon capture must be part of the solution.

VOLKER SICK *PROFESSOR, MECHANICAL ENGINEERING, UNIVERSITY OF MICHIGAN, AND DIRECTOR, GLOBAL* CO_2 *INITIATIVE*

ORESKES REPLIES: *My argument isn't against trying to find uses for carbon. If we could make CCU work, that would be great. Folks have been talking about it for decades, however, and no one has yet found ways to do it profitably. My argument is about focus and particularly about how we use taxpayer dollars.*

If private-sector actors have ideas for capturing, storing or using carbon, I'm all for that. But they should invest their own money. We should focus taxpayer funds on what we know works: replacing fossil fuels with energy efficiency and renewables. We are paying now for climate damages. We should not also be expected to pay for the industry's waste products.

ERRATA

"The Great Eclipse," by Rebecca Boyle, incorrectly referred to the sun's outermost layers as including "the chromosphere (the transition region)." The chromosphere and the transition region are separate layers.

"A Safe and Just Earth," by Joyeeta Gupta and InfoDesignLab, should have described the World Health Organization's standards for fine-particulate pollution in terms of micrograms per cubic meter, not micrograms per square meter.

In “When We Find Earth 2.0, What’s Next?” by Phil Plait [The Universe, May], the illustration of an Earth-size exoplanet should have been credited to Aaron Alien/Alamy Stock Photo.

Aaron Shattuck is a senior copy editor at *Scientific American*.

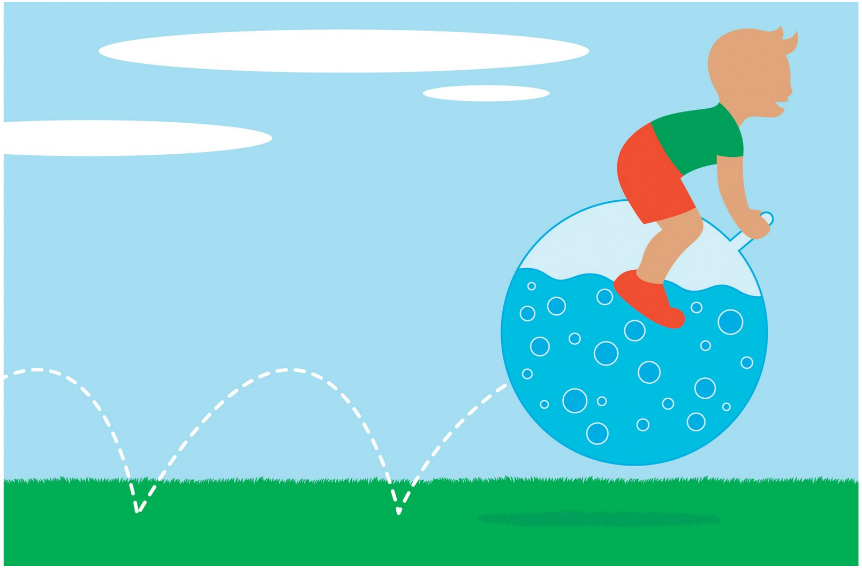
Engineering

- **Tiny Spheres Key to Tunable ‘Smart Liquid’**
  Programmable liquids could aid robot grippers, shock absorption, acoustics, and more

Tiny Spheres Key to Tunable ‘Smart Liquid’

Programmable liquids could aid robot grippers, shock absorption, acoustics, and more

By Simon Makin



Thomas Fuchs

Pneumatic and hydraulic systems use pressurized gases and liquids, respectively, to carry out countless crucial mechanical tasks. Each has distinct pros and cons: pneumatic systems are springy and thus less vulnerable to shock damage; hydraulic ones offer more precision and power. This is because gases are compressible, whereas liquids are not. But “there’s nothing in between, naturally speaking,” says Adel Djellouli, an applied physicist at Harvard University. “Our idea was to occupy this middle space and make artificial liquids with programmable compressibility.”

In *Nature*, Djellouli and his colleagues describe testing a new “meta fluid” composed of tiny, air-filled silicone rubber spheres suspended in liquid. This fluid’s compressibility, viscosity and transparency are all programmable. Potential applications include smart shock absorbers, advanced e-inks and programmable sound baffles.

The mechanism is simple: At certain pressures, the spheres buckle and let the liquid become more compressed. The spheres' size, thickness, softness and number can be adjusted to tune various properties under pressure. Djellouli and his team demonstrated the fluid's versatility by putting it in a hydraulic robot gripper to grasp objects of differing size and fragility: a glass bottle, an egg and a blueberry. The researchers used the same amount of fluid in the system to close the gripper on each object without crushing it.

"We tuned the springiness of our fluid so that whether it's something big and rigid or small and fragile, the gripper can safely grab it," Djellouli says. This strategy could endow conventional robots with capabilities previously limited to more specialized "soft" robots.

Air in the spheres scatters light, the researchers found, making the liquid opaque like foamy water—but buckled spheres scatter less, making it transparent. Easy switching between states could contribute to quick-response e-inks. Buckled spheres also make the fluid more viscous because they can no longer roll around one another freely. This property could be useful in developing tunable vibration-damping systems, says Robert Shepherd, who builds advanced robots at Cornell University. “The more viscous something is, the more energy it dissipates,” he says.

A 2022 study described a similar fluid using collapsible, straw-shaped capsules, Shepherd adds, but with a crucial difference. “The straws were quite large, so flowing through small orifices wasn’t [possible],” Shepherd says. The new spheres are “a pretty cool advance.”

Additional abilities have yet to be investigated. The fluid’s thermodynamic properties may be useful for energy storage, and Djellouli says he is currently exploring acoustic possibilities: “You can tune a meta fluid so it blocks specific frequencies,” such as speech—and then lets them through at the flick of a switch.

Simon Makin is a freelance science journalist based in the U.K. His work has appeared in *New Scientist*, the *Economist*, *Scientific American* and *Nature*, among others. He covers the life sciences and specializes in neuroscience, psychology and mental health. Follow Makin on X (formerly Twitter) @SimonMakin

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Evolution

- **Glow-in-the-Dark Animals May Have Been around for 540 Million Years**
  Ancestors of so-called soft corals may have developed bioluminescence in the earliest days of deep-ocean living

Glow-in-the-Dark Animals May Have Been around for 540 Million Years

Ancestors of so-called soft corals may have developed bioluminescence in the earliest days of deep-ocean living

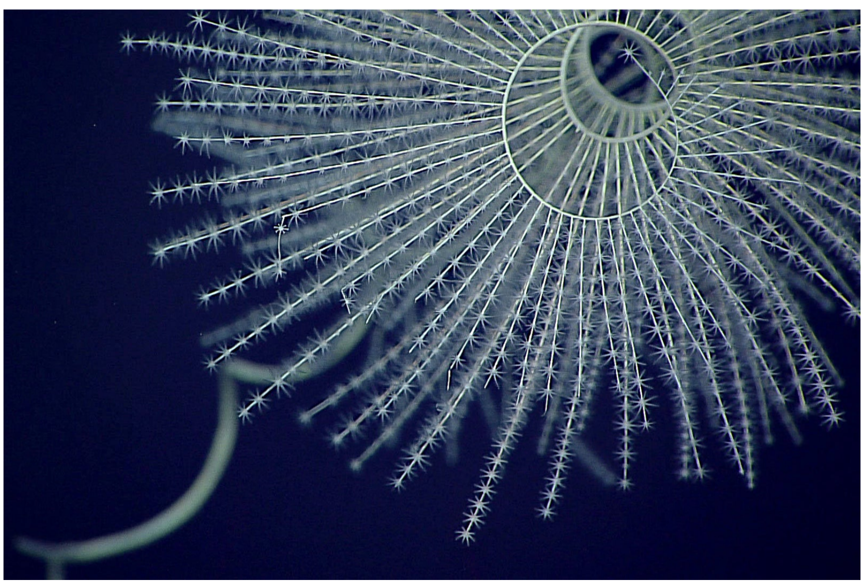
By Meghan Bartels

Soft coral off the northwestern Hawaiian Islands.
NOAA

The more humans have explored the deep oceans, the more examples we've found of animals with a seemingly magical talent: bioluminescence, the ability to produce their own light.

Bioluminescence is surprisingly common, with various mechanisms having evolved perhaps around 100 separate times over the course of hundreds of millions of years. New research published in the *Proceedings of the Royal Society B* traces bioluminescence in the family tree of unusual animals called octocorals and suggests that the phenomenon may have evolved in the sea more than 500 million years ago—thereby making its first known emergence more than twice as old as previously calculated.

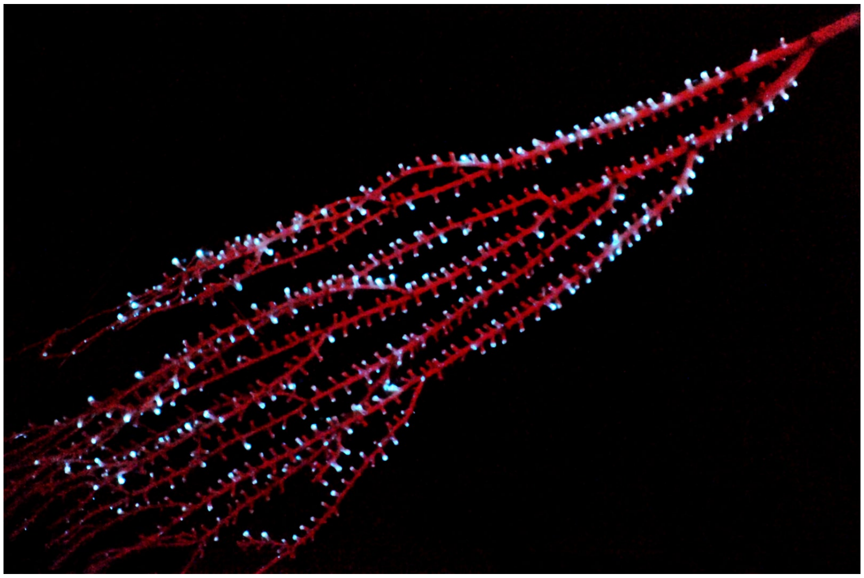
For animals, especially those that live deeper in the ocean than sunlight can reach, bioluminescence can make the difference between life and death: for example, it can lure prey and deter predators. Biologists are still working to understand the full scope of the phenomenon's uses. "We've explored so little of our own planet, and there could be so many more organisms down there that are using light in ways we haven't even begun to understand yet," says marine biologist Edith Widder, who is CEO and a senior scientist at the nonprofit Ocean Research & Conservation Association. "That's what intrigues me the most about bioluminescence: how animals use it to survive."



A deep-sea bioluminescent soft coral called *Iridogorgia magnispiralis*.
NOAA Office of Ocean Exploration and Research/Deepwater Wonders of Wake

But despite its ubiquity today, past bioluminescence is remarkably difficult to study because it rarely leaves a trace in fossils—when fossils even remain. The octocoral varieties called soft corals, for instance, don't form the massive, rocklike reefs that coral is typically known for. Instead they build colonies by excreting a soft structure embedded with tiny chips of skeletonlike material. This body type means that soft corals leave behind only the tiniest of fossils, a challenge for scientists who try to peer into their histories.

Still, zoologist Andrea Quattrini, curator of corals at the National Museum of Natural History in Washington, D.C., and her colleagues were determined to understand how—and when—bioluminescence may have developed in octocorals. Quattrini has spent about a decade testing living octocorals collected from the ocean by sequestering the creatures under a blanket or in a dark room and nudging them with a pair of laboratory tweezers, looking for signs of light.

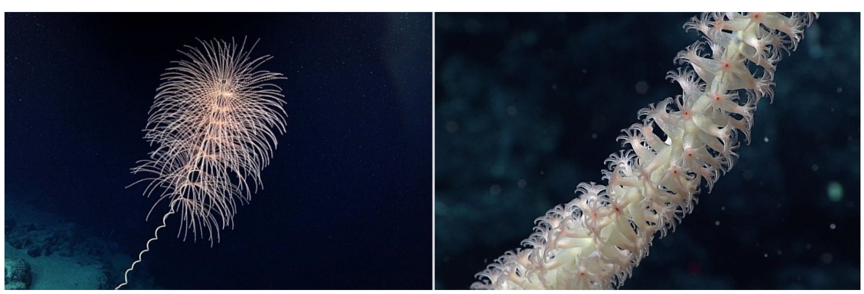


A bioluminescent bamboo coral (a type of soft coral) called *Isidella* that was collected in the Bahamas.
Sönke Johnsen

Quattrini's team mapped such results in an evolutionary tree that shows how different modern octocorals are related to one another, letting the scientists look for patterns in which branches can and can't create light. By searching for the simplest possible evolutionary story to match these observations, the researchers concluded that bioluminescence most likely evolved just once in these animals. Then they used the rare fossils that have been confidently identified as belonging to specific octocoral types to root the tree in time. The analysis suggests the first known evolution of bioluminescence in a marine environment occurred some 540 million years ago—much longer ago than previous estimates of 267 million years.

The proposed date falls just before or during an event that paleontologists have dubbed the Cambrian explosion, when a burst of biological diversification occurred. It was likely also around that time that animals first moved from the shallow oceans into the depths where sunlight doesn't penetrate. This timeline for developing bioluminescence makes sense, say Quattrini and Widder, who both note that rudimentary light sensors also developed around this time. In this context, bioluminescence became a communicative tool for corals to use to confuse prey or startle predators, like "a burglar alarm," Quattrini says.

"I think our study really points to the fact that it's one of the earliest forms of communication in the oceans—maybe one of the earliest forms of communication on Earth, really," Quattrini says. "It's a fascinating form of communication that's really quite simple at its core."



A deep-sea bioluminescent octocoral of the genus *Iridogorgia* (*left*). A bioluminescent keratoisidid bamboo coral found in the deep ocean off the coast of Hawaii (*right*).
NOAA Office of Ocean Exploration and Research

Yuichi Oba, a biologist at Chubu University in Japan, who has studied bioluminescence but was not involved in the new research, says he would like to see more caution taken with the determination that octocoral bioluminescence didn't arise independently multiple times. If it did, that would make the phenomenon more recent than the new analysis says—perhaps just

400 million to 200 million years old, Oba suggests. Quattrini says the shared mechanism for bioluminescence across octocorals supports the idea of a single evolution.

Quattrini and her colleagues next plan to analyze the gene that builds luciferase, the protein responsible for bioluminescence in octocorals. The same gene shows up in both bioluminescent and nonbioluminescent octocorals, she says, so the researchers want to understand how some of the animals seem to have lost the ability to light up.

This kind of work helps to paint a better picture of what the ecosystems of the ancient Earth—which seem so alien to us today—may have looked like. “Imagine the ocean where coral emit light and carnivorous predators have large eyes in midnight water,” Oba says. “Life is wonderful.”

Meghan Bartels is a science journalist based in New York City. She joined *Scientific American* in 2023 and is now a senior news reporter there. Previously, she spent more than four years as a writer and editor at Space.com, as well as nearly a year as a science reporter at *Newsweek*, where she focused on space and Earth science. Her writing has also appeared in *Audubon*, *Nautilus*, *Astronomy* and *Smithsonian*, among other publications. She attended Georgetown University and earned a master’s degree in journalism at New York University’s Science, Health and Environmental Reporting Program.

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Fossil Fuels

- **The Gas Industry Is Gaslighting the Public about Climate Change**
  A fossil-fuel executive blames consumers for the climate crisis

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The Gas Industry Is Gaslighting the Public about Climate Change

A fossil-fuel executive blames consumers for the climate crisis

By Naomi Oreskes

Scott Brundage

In March 1969 Senator Henry M. Jackson of Washington State received a letter from an incensed constituent. The letter writer had watched an episode of a television talk show where the Beat poet Allen Ginsberg claimed that “the current rate of air pollution brought about by the proliferation of automobiles” could cause “the rapid buildup of heat on the earth.” This would melt the polar ice caps and eventually flood “the greater part of the globe.”

The constituent wanted the powerful senator to stop Ginsberg—one of America’s “premier kooks,” in his opinion—from spouting such nonsense, but the senator soon learned that it wasn’t nonsense. Jackson reached out to presidential science adviser Lee DuBridge, who affirmed that Americans were “filling the atmosphere with a great many gases and in very large quantities from our automobiles” and that these gases could indeed melt the ice caps and radically change the climate. It was of “great importance,” DuBridge explained, that we learned more about carbon dioxide and its impacts “before discovering them too late and perhaps to our sorrow.”

If you are surprised to learn that scientists have been warning about the dangers of greenhouse gases for more than half a century, you are not alone. The fossil-fuel industry has worked for decades to deny both climate science and its own history. Its latest move is to blame consumers for the climate crisis.

Ginsberg may have learned about the threat of anthropogenic climate change from *The Unchained Goddess*, a 1958 made-for-television movie produced by Frank Capra, one of America’s most famous filmmakers. The film featured “Dr. Research” (Frank Baxter, a professor at the University of Southern California) explaining that although scientists might one day be able to control both weather and climate, these were dangerous aspirations because “with our present knowledge we have no idea what would happen.” Even a few degrees of temperature increase could lead to enough sea-level rise that an “inland sea would fill a good portion of the Mississippi Valley,” and tourists in “glass bottom boats would be viewing the drowned towers of Miami through 150 feet of tropical water.” “Even now,” Dr. Research explained, “man may be unwittingly changing the world’s climate through the waste products of his civilization," including "more than six billion tons of carbon dioxide" every year.

Ginsberg might also have learned about climate change from the *New York Times*, *Fortune* magazine, *Time* magazine or the children's *Weekly Reader,* all of whom published popular articles on the topic. At the 1965 annual meeting of the American Petroleum Institute, the institute's president specifically linked climate change to cars, which might force Americans to find alternatives to internal-combustion engines in automobiles. There was "still time to save the world's peoples from the catastrophic consequence of pollution," he asserted, "but time is running out."

These various discussions eventually led to the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and four years later to the United Nations Framework Convention on Climate Change committing its signatories to preventing "dangerous anthropogenic interference with the climate system." Yet it wasn't until last year that the U.S. federal government finally passed a bill to fight climate change.

This bill, the Inflation Reduction Act, offers a variety of strategies to support renewable energy, such as tax credits for utility-scale renewable energy, federal investment in rural electricity co-ops, and rebates for consumers who install energy-efficient heat pumps, windows or rooftop solar panels. According to the Department of Energy, "it's the single largest investment in climate and energy in American history," and it's expected to cut our greenhouse gas emissions by around 40 percent by 2030 compared with 2005 levels. But the history of events leading up to the bill's passage raises a big question: Why has it taken so long for us to act on this problem?

Recently the CEO of ExxonMobil suggested that the public is to blame. In an interview with *Fortune* in February, Darren Woods claimed that the main reason the world has waited too long to act on climate is that consumers are just not willing to pay for carbon reduction.

This is flat-out false. For one thing, renewable energy is now cheaper than fossil fuels in most places Moreover, poll after poll has shown that most Americans are worried about climate change and are willing to pay to do something about it. In a Gallup poll conducted earlier this year, 74 percent of respondents ranked climate change as either “critical” or “important” to the “vital interests of the United States.” A 2018 University of Chicago study found that two thirds of Americans would support a carbon tax if the proceeds were used for environmental restoration. A 2024 international study found that a whopping 69 percent of respondents would be willing to contribute at least *1 percent of their income* to tackle climate change.

ExxonMobil spent years telling the public that climate change was highly uncertain even as the corporation’s own scientists were making accurate predictions about future carbon dioxide levels and the global warming they would cause. These days the industry is promoting false “solutions,” such as removing carbon from the atmosphere, which is extremely costly and hard to scale and which won’t work in any case if we keep using fossil fuels (because the removed carbon will just be replaced by new carbon). But this is what the industry intends for us to do. We know this is true because they are still exploring for yet more oil and gas, fuels that scientists tell us we cannot afford to burn.

In 1959 Esso (Exxon’s original name) debuted the slogan “Put a tiger in your tank,” and for decades the industry never changed its stripes. Now it evidently has: from denying that climate change is a problem to admitting that it is a problem but blaming the public for it. The industry that gave us gas for lighting is gaslighting us.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific

American.

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

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History

- **July/August 2024: Science History from 50, 100 and 150 Years Ago**
  Death rays; the sawfly’s barf defense

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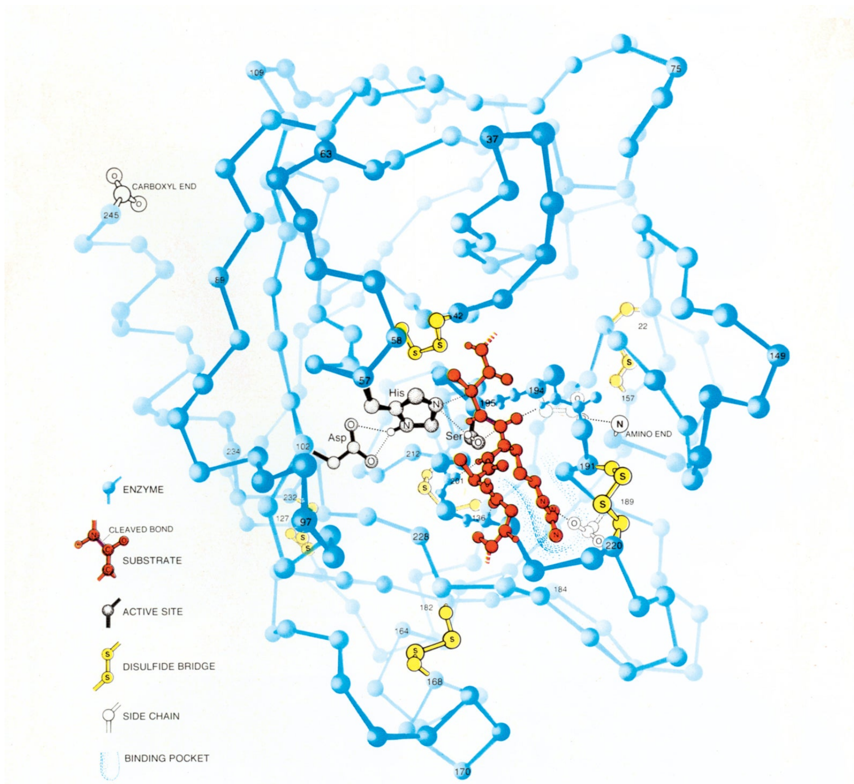
July/August 2024: Science History from 50, 100 and 150 Years Ago

Death rays; the sawfly's barf defense

By Mark Fischetti



1974, Protein Cutter: "Trypsin and a substrate fit together like pieces of a three-dimensional jigsaw puzzle." Trypsin is an enzyme that aids with digestion by breaking chains of amino acids in proteins. *Scientific American*, Vol. 231, No. 1; July 1974

1974

The Sawfly's Barf Defense

"Many insects regurgitate or defecate when they are threatened, a phenomenon familiar to almost anyone who has held a grasshopper in their hand. It is believed that such discharges help to protect the insect against predation. When the larva of the sawfly is disturbed, it quickly turns and dabs a droplet of a viscous resin from its mouth on the offending object. This oral effluent is obnoxious to many predators; ants and spiders promptly flee. The sawfly larva feeds on the needles of conifers, including the lower portion, which contains resin from the branch. The resin repels other insects, part of the tree's own defenses against attack."

On supporting science journalism

1924

Death Rays No One Knows

"Every so often we are startled by reports of a new ray with strange and terrifying properties, intended for such gentle tasks as paralyzing airplanes in flight, blowing up battleships and killing enemy troops by the wholesale. The mysterious ray is a true perennial of science. It was talked about when Nikola Tesla experimented with high-frequency currents in 1898 and put out of commission the generators in a power house several miles away. Almost a year ago a French inventor is said to have demonstrated a mysterious ray which caused Parisian taxicabs to stop. Recently, the garrulous Leon Trotsky has told the world to beware of a new Russian death ray. Guglielmo Marconi, from time to time, has been working on some mysterious ray for destructive purposes, according to rumor. What are these diabolic rays? No one except their sponsors really knows. We are given no proof, except a few unimpressive laboratory experiments. Groping about in pitch blackness, we are frankly, skeptical."

1874

Perils of Nitroglycerin

“Nitroglycerin is a thick, colorless oil. People are so accustomed to handling oils that it is almost impossible to make them realize the danger that lurks even in the smallest quantity of nitroglycerin. It explodes when gently struck, and is 10 times more powerful as an explosive than gunpowder. The other evening, in Jersey City, a gentleman and lady were taking a moonlight stroll in the vicinity of one of the shafts of the new Delaware and Lackawanna railway tunnel. The man saw on the ground the glimmer of a small tube, picked it up, and slapped it from one hand to the other, when a terrific explosion ensued. His eyes were destroyed, his limbs broken, and his companion was dreadfully injured. It was a discarded nitroglycerin tube, such as are used in blasting, and is supposed to have been thrown away.”

Oxygen Centennial

“We have alluded to the proposition of Dr. H. Carrington Bolton, of Columbia College, of a reunion of chemists to celebrate the hundredth anniversary of the birth of modern chemistry, that event being fixed in 1774, owing to the discoveries, at that time, of oxygen by Joseph Priestley, chlorine by Carl Wilhelm Scheele and other important investigations by Antoine Lavoisier. The day set apart is August 1, in Northumberland, Pa., where Priestley’s remains are buried.”

Prohibition, 46 Years Hence

“There is a substance that has been the cause of more sorrow, crime and suffering than all other evil agencies that have afflicted the world. It has caused tens of thousands of murders and uncounted instances of robbery, theft, arson and suicide; it has brought misery and want into millions of households. What an awful indictment against a substance which stands so closely allied in chemical relationship to innocent sugar! Alcohol is not a natural product; it can only result from a ferment. If this chemicaI change had been impossible, the human race would have been saved from shedding tears, the aggregated volume of which reaches that of a mighty river. We unhesitatingly declare that the world in its present advanced stage has no need of alcohol. Why not then make a determined effort to rid the country and the world of the monster? There is virtue and moral force enough to compel Congress to prohibit its importation, and enough in most States to compel legislatures to prohibit its manufacture."

In the U.S., prohibition of the manufacture, transport and sale of alcohol lasted from 1920 to 1933.

Mark Fischetti has been a senior editor at *Scientific American* for 17 years and has covered sustainability issues, including climate, weather, environment, energy, food, water, biodiversity, population, and more. He assigns and edits feature articles, commentaries and news by journalists and scientists and also writes in those formats. He edits History, the magazine's department looking at science advances throughout time. He was founding managing editor of two spinoff magazines: *Scientific American Mind* and *Scientific American Earth 3.0*. His 2001 freelance article for the magazine, "Drowning New Orleans," predicted the widespread disaster that a storm like Hurricane Katrina would impose on the city. His video *What Happens to Your Body after You Die?*, has more than 12 million views on YouTube. Fischetti has written freelance articles for the *New York Times, Sports Illustrated, Smithsonian, Technology Review, Fast Company,* and many others. He co-authored the book *Weaving the Web* with Tim Berners-Lee, inventor of the World Wide Web, which tells the real story of how the Web was created. He also co-authored *The New Killer Diseases* with microbiologist Elinor Levy. Fischetti is a former managing editor of *IEEE Spectrum Magazine* and of *Family Business Magazine*. He has a physics degree and has twice served as the Attaway Fellow in Civic Culture at Centenary College of Louisiana, which awarded him an honorary doctorate. In 2021 he received the American Geophysical Union's Robert C. Cowen Award for Sustained Achievement in Science Journalism, which celebrates a career of outstanding reporting on the Earth and space sciences. He has appeared on NBC's Meet the Press, CNN, the History Channel, NPR News and many news radio stations. Follow Fischetti on X (formerly Twitter) @markfischetti

Internet

- **We Need a Public Service Internet to Free Us from Big Tech’s Grasp**
  The profit-led business models of big tech are harming democracy. We should look to the tradition of public media to help us find alternatives

We Need a Public Service Internet to Free Us from Big Tech’s Grasp

The profit-led business models of big tech are harming democracy. We should look to the tradition of public media to help us find alternatives

By Helen Jay

Jovana Mugoša

“Big tech”—aka Google, Facebook, Apple, Microsoft—now outdoes the notorious trusts of the Gilded Age in their raw power. Much of it rests in the hands of some of the wealthiest men in the world. They share not just vast reach and influence, but a common thirst for maximum profit, to the detriment of the public interest.

We’ve seen the results, now too familiar, in everything from a widespread adolescent mental health crisis to increased political polarization. Critics such as Shoshana Zuboff, Tim Wu and Siva Vaidhyanathan, as well as Facebook whistleblower Frances

Haugen's October testimony on the ways in which Facebook's leadership repeatedly prioritized profit over safety decisions, have focused on the direct relationship between big tech's rapacious profit-seeking business model and subsequent civic and individual harms. For them, far from isolated incidents of errors and misjudgement, the damage caused by digital platforms—ranging from anxiety to extremism to loss of privacy to misinformation—is evidence of a malignant profit system working. It is the natural consequence of the way digital businesses now work, where they encourage platform users to stay as long as possible on their sites in order to monetize their attention. Crucially, there is evidence that divisive, emotional and potentially harmful content drives attention online, and therefore not only are companies not incentivized to remove harmful content, they are actually incentivized to promote it—regardless of the ramifications. Political scientist Francis Fukuyama expands on the democratic implications of this—arguing in the *Journal of Democracy* that it is "unsurprising that these platforms have been blamed for propagating conspiracy theories, slander, and other toxic forms of viral content: This is what sells."

The social and democratic impacts show no sign of abating. Indeed, the rapid development of generative AI technologies may intensify technology's influence on domains as varied as culture, business, politics, health and education. The risks posed are even more extreme—from increased market concentration to election fraud to even the demise of the human race.

On supporting science journalism

We should not be content to leave the prospects for democracy, the labor market and humanity's existence in the hands of billionaire tech moguls. We need an Internet that instead puts the public and democracy first.

The past can offer us a guide to an alternative route forward. In the U.K., public service broadcasting has dominated the airwaves since the creation of the BBC in 1922.The original vision of John Reith, the BBC's first director-general, was to use the power of broadcasting for a moral purpose—to "inform, educate and entertain." In contrast to rules-based regulation that protects individuals against harms, public service broadcasting is explicitly set up to deliver "positive" goals—such as informed citizenship, trusted information, equal access to knowledge, cultural diversity, equity and representation and shared cultures and identities. These goals are delivered through a mix of public ownership, public funding and regulatory obligations for specific broadcasting institutions—for example to produce a certain amount of news and current affairs programs.

Other countries take different approaches. In the U.S., for example, PBS receives more of its income from philanthropy, and focuses more narrowly on serving "market failure" genres such as news, documentaries and children's programming, as opposed to broader entertainment. Whatever the approach, public service broadcasting across the world treats the audience first and foremost as citizens participating in a society, rather than as consumers in a marketplace.

This isn't how big tech sees us. It is a widely held view within social science that technology is never neutral; it is always shaped by political, social and economic forces as well as human values and choices. The birth of the Internet was heavily influenced by the libertarian philosophies of early Silicon Valley founders, and our current approach to technology regulation has been predominantly shaped by neoliberal desires to favor economic growth and consumerism. These ideologies should not determine the limits of our imagination, however. Given all that is at stake, it is time to ask whether public service–based business models could provide better outcomes—for democracy and citizens.

There are many different ideas for what a “public service Internet” might look like. For example, media scholar Ethan Zuckerman has established the Initiative for Digital Public Infrastructure, which aims to build and research digital tools, including social networks, that promote civic goals rather than commercial ones. Public broadcasters from Belgium, Canada, Germany and Switzerland have collaborated with nonprofit organization New Public to form a “public spaces incubator,” which is aimed at identifying formats and tools that will encourage positive, meaningful online conversations that are free of abuse and harassment—in contrast to those offered by the commercial platforms. Political economist Victor Pickard advocates for the development of public media centers that can operate as anchor institutions to deliver news and journalism across digital platforms. Other proposals in the field include technological solutions such as more ethical software standards, regulatory reforms such as how to develop “public utilities” obligations, and structural changes such as the development of alternative models of ownership such as “platform cooperatives” or “digital commons,” or the creation of new publicly owned and funded institutions. However, these are now typically disparate, self-initiated projects and ideas—rather than policy-designed interventions with incentives, scale or funding attached.

Whatever form it takes, we need a public service approach that proactively supports the development of nontoxic search and social media spaces, in which users have access to diverse, high-quality knowledge, culture and social connections without being required to turn themselves into products in return.

Technology policy in the U.S., U.K. and elsewhere has to date been predominantly reactive—trying to limit the harms caused by platforms—rather than proactively articulating a forward-looking vision in which technology nurtures and supports our civic values. It is time to be more intentional about the kind of role we want digital platforms to play in our lives. Public service broadcasting reminds us that policy makers around the world have acted in the past to develop a philosophy for technology that puts people over profit. We must once again do so to deliver a public service Internet.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

A version of this article with the title "We Need a Public Service Internet" was adapted for inclusion in the July/August 2024 issue of Scientific American.

Helen Jay is a doctoral candidate at the University of Westminster in England. She was formerly head of policy and corporate affairs at Channel 4, one of the U.K.'s leading public service broadcasters.

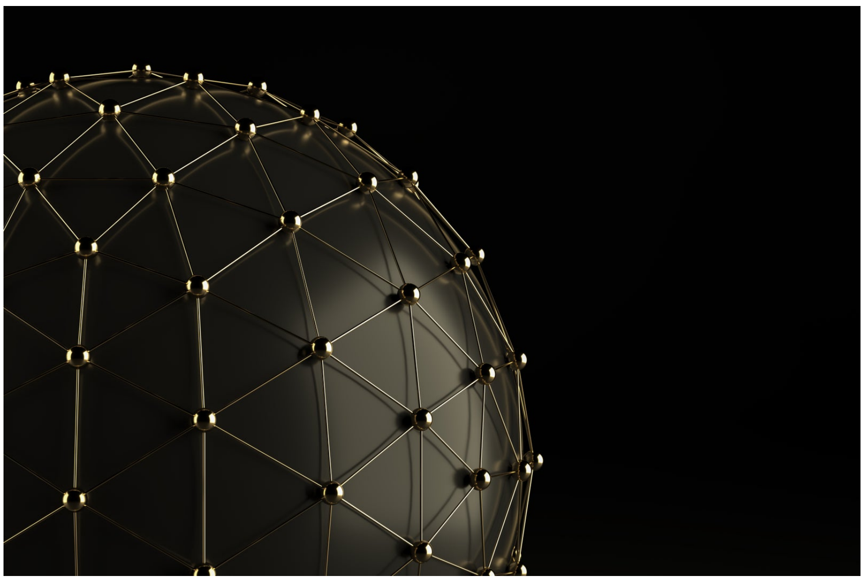
Materials Science

- **Atom-Thick Gold Coating Sparks Scientific ‘Goldene Rush’**
  Ultrathin gold was achieved with the help of a century-old sword-making technique
- **‘Self-Cleaning’ Paint Breaks Down Pollutants on Surfaces and Perhaps Nearby Air**
  Recycled materials contribute to a pollutant-neutralizing paint

Atom-Thick Gold Coating Sparks Scientific 'Goldene Rush'

Ultrathin gold was achieved with the help of a century-old sword-making technique

By Rachel Nuwer



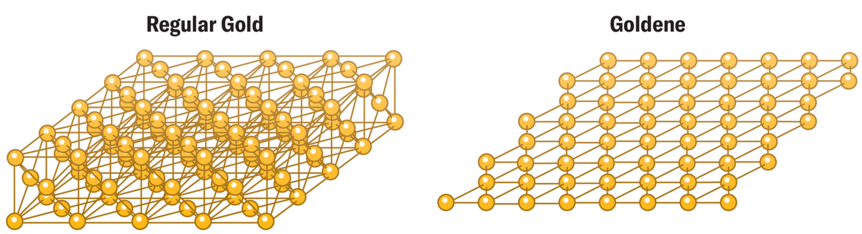
Akinbostanci/Getty Images

A glitzy holy grail in materials science has just been attained: scientists have created freestanding, single-atom-thick sheets of gold. This achievement is the first of its kind with any metal atoms, which seem to abhor flatness and typically insist on clustering into droplets or particles.

The method behind the new monolayer metal, dubbed goldene, could "expand the boundaries of what it's possible to do with materials," says Lars Hultman, a materials scientist at Linköping University in Sweden and senior author on a new study *in Nature Synthesis* on the technique. Gold is of particular interest, he adds, because its nanoparticles are already used in electronics, photonics, sensing, biomedicine, and more. The researchers expect that goldene will exhibit its own intriguing suite of new properties, like the single-atom sheets of carbon known as graphene have.

This latest breakthrough builds on previous work in which Hultman and his colleagues embedded gold atoms inside titanium silicon carbide by heating layered films of the materials to about 670 degrees Celsius, causing gold to displace some of the silicon. “The good news was that we had gold layers that were just one atom thick,” Hultman says. “The bad news was that they were stuck inside the host crystal.”

On supporting science journalism



Amanda Montañez; Source: “Synthesis of Goldene Comprising Single-Atom Layer Gold,” by Shun Kashiwaya et al., in *Nature Synthesis*. Published online April 16, 2024 (*reference*)

After years of brainstorming how to remove the base material casing—called exfoliation—while preserving the delicate sheets of gold inside, Hultman and his colleagues followed a promising lead with Murakami’s reagent, a solution used in a century-old technique for etching Japanese swords and other metals. But the first attempts to use the reagent were “a total failure,” Hultman says. The gold and base material kept dissolving.

Lead study author Shun Kashiwaya, a materials scientist at Linköping, turned to another piece of “100-year-old wisdom” to find the answer: a 1905 German article describing one of the reagent’s components, light-activated cyanide, which suggested applying the reagent in the dark could be key. After finding this vital clue, Kashiwaya says, “immediately I started to feel hopeful that exfoliation might work in darkness.”

He was right: the team managed to produce freestanding goldene flakes of about a tenth of a micron in area. The researchers also confirmed that the goldene has a higher binding energy than regular gold; this should help expand its ability to catalyze or jump-start chemical reactions. They plan to further explore goldene’s properties and ways to apply their method to other metals.

The new work “offers an exciting perspective for the development of 2D metals and understanding their properties,” says Yury Gogotsi, a materials scientist at Drexel University, who was not involved in the research. He adds that goldene “should be studied for potential catalysis and other applications.”

Rachel Nuwer is a science journalist and author. Her latest book is *I Feel Love: MDMA and the Quest for Connection in a Fractured World* (Bloomsbury, 2023). Follow her on X @RachelNuwer

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This Paint Could Clean Both Itself and the Air

Recycled materials contribute to a pollutant-neutralizing paint

By Kate Graham-Shaw


Thomas Fuchs

The pollutants clogging our skies aren’t just a health risk; they also cause ugly stains on buildings and other structures. To combat this, chemists have been working for years on a special type of paint that not only can clean itself but also may remove pollutants from the air.

This technology uses titanium oxide nanoparticles that jump-start chemical reactions. When an artificial ultraviolet light source shines on the paint, the nanoparticles react with pollutants to make them break down—theoretically removing them from nearby air and preventing a discoloring buildup. Companies already offer these so-called photocatalytic paints, but some chemists remain cautious about the products’ effectiveness and sustainability.

For a recent study in *American Chemical Society Catalysis*, researchers developed a new photocatalytic paint they claim works using UV rays from ordinary sunlight, making its self-cleaning properties easier to activate. They’ve also shown they can effectively produce this paint from recycled materials.

“One of the goals was that we minimize the use of synthetic reagents,” says study co-author Qaisar Maqbool, a chemist at the Vienna University of Technology. “We do this by using waste material like titanium scrap from industry and also using fallen leaves, which are organic waste.”

In photocatalysis, UV light excites the electrons in the titanium oxide nanoparticles, which interact with airborne water molecules to produce highly reactive hydroxyl radicals. These unstable chemicals attack pollutants that come in contact with the paint, converting them into less harmful substances such as carbon dioxide and water. The research team added phosphorus, nitrogen, carbon, and other elements to the nanoparticles’ structure, which reduced the amount of energy needed to spark the reaction and let it work via ordinary sunlight. In laboratory tests, these modified nanoparticles removed up to 96 percent of tested pollutants added to the paint’s surface.

“It is better to be able to use solar light to activate, as the paint can work passively, by itself,” says Antonio Nieto-Márquez Ballesteros, a chemist at the Technical University of Madrid. But a real-world setting would probably reduce its effectiveness, he adds.

“Under laboratory conditions, it is a very small scale, and everything is very well controlled—all the parameters, such as temperature, humidity, flow rate of reactance or the concentration of pollutants—but you will never get those results at a real scale.”

The study authors stress that this work is just an initial step in their research. “I think it’s a very fundamental study,” says co-author Günther Rupprechter, a chemist at the Vienna University of Technology. Future research will confirm how effectively pollutants are neutralized from the air itself. “We don’t claim that we can remove all contamination from air,” he says, “but overall, it looks promising.”

Kate Graham-Shaw is a journalist based in New York City. She covers international news for Japanese media and also covers health and science topics as a freelancer.

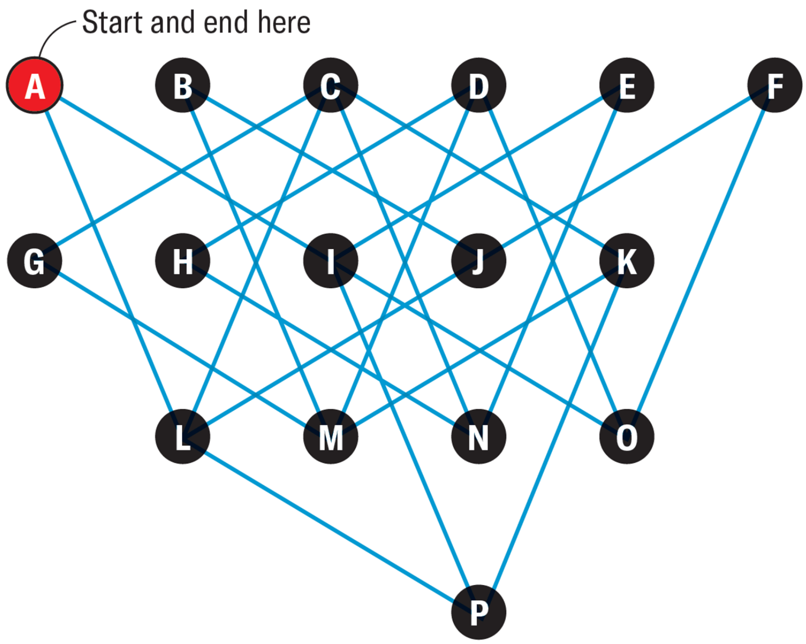
Mathematics

- **Help a Traveling Salesman Find Every Route in this Math Puzzle**
  Try to solve a traveling salesman’s directional dilemma
- **How the Guinness Brewery Invented the Most Important Statistical Method in Science**
  The most common test of statistical significance originated from the Guinness brewery. Here’s how it works

Math Puzzle: How Many Routes Can You Find?

Try to solve a traveling salesman's directional dilemma

By Heinrich Hemme



Henry Ernest Dudeney may be among the most significant puzzle inventors who ever lived. He was born in Mayfield, England, in 1857, the son of a village schoolteacher, and he died in 1930. Dudeney designed brainteasers for newspapers and magazines regularly for decades, and he later compiled most of his puzzles into books. This head-scratcher comes from his 1917 book *Amusements in Mathematics*.

A traveling salesman who lives in city A wants to visit all cities from B to P over the course of a week, though not necessarily in alphabetical order, and return to A at the end. He plans to enter each city exactly once. The blue lines are the only roads connecting the 16 cities. The traveling salesman may use only a straight route between any two cities; he is not allowed to turn at the intersection of two streets. How many different routes are possible?

View puzzle with solution at this link.

On supporting science journalism

Editor's Note: The version of the puzzle that appeared in the print edition of the July/August 2024 issue incorrectly included connections between C and I and between I and M. The error did not impact the solution.

Heinrich Hemme is a physicist and a former university lecturer at FH Aachen–University of Applied Sciences in Germany.

How the Guinness Brewery Invented the Most Important Statistical Method in Science

The most common test of statistical significance originated from the Guinness brewery. Here’s how it works

By Jack Murtagh

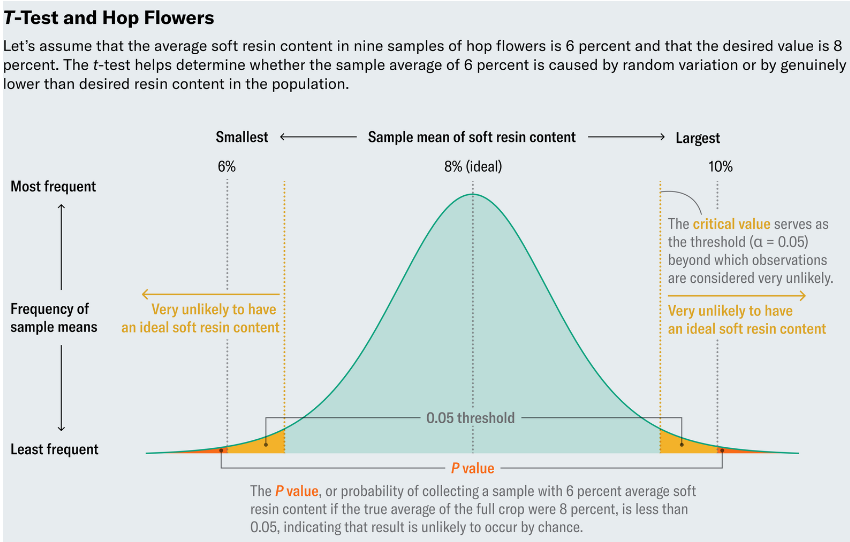
The gates of the Guinness Saint James Gate Brewery stand in Dublin, Ireland.
Hollie Adams/Bloomberg via Getty Images

“One Guinness, please!” a customer says to a barkeep, who flips a branded pint glass and catches it under the tap. The barkeep begins a multistep pour process lasting precisely 119.5 seconds, which, whether it’s a marketing gimmick or a marvel of alcohol engineering, has become a beloved ritual in pubs worldwide. The result: a rich stout with a perfect layer of froth like an earthy milkshake.

The Guinness brewery has been known for innovative methods ever since its founder, Arthur Guinness, signed a 9,000-year lease in Dublin for £45 a year. For example, after four years of tinkering, Michael Edward Ash, a mathematician turned brewer there, invented a chemical technique that gives the brewery’s namesake stout its velvety head. The method, which involves adding nitrogen gas to kegs and to little balls inside cans of Guinness, led to today's hugely popular "nitro brew" styles of beer and coffee.

But the most influential innovation by far to come out of the brewery has nothing to do with beer. It was the birthplace of the *t*-test, one of the most important statistical techniques in all of science. When scientists declare their findings "statistically significant," a *t*-test is very often the basis for that determination. How does this work, and why did it originate in beer brewing of all places?

Near the start of the 20th century, Guinness had been in operation for almost 150 years and towered over its competitors as the world's largest brewery. Until then, quality control on its products had consisted of rough eyeballing and smell tests. But the demands of global expansion motivated Guinness leaders to revamp their approach to target consistency and industrial-grade rigor. The company hired a team of brainiacs and gave them latitude to pursue research questions in service of the perfect brew. The brewery became a hub of experimentation to answer an array of questions: Where do the best barley varieties grow? What is the ideal saccharine level in malt extract? How much did the latest ad campaign increase sales?

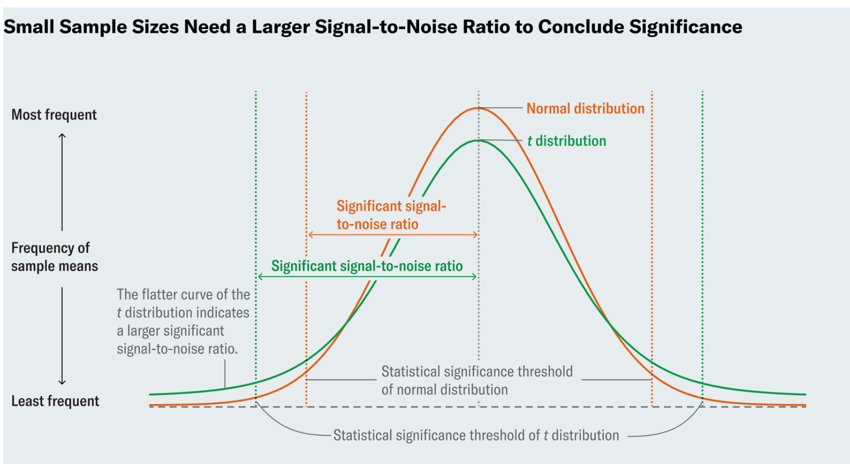


Shuyao Xiao

Amid the flurry of scientific energy, the team faced a persistent problem: interpreting its data in the face of small sample sizes. One challenge the brewers confronted involves hop flowers, essential ingredients in Guinness that impart a bitter flavor and act as a natural preservative. To assess the quality of hops, brewers measured the plants' soft resin content. Let's say they deemed 8 percent a good and typical value. Testing every flower in the crop wasn't economically viable, however. So they did what any good scientist would do and tested random samples of flowers.

Let's inspect a made-up example. Suppose we measure the soft resin content of nine samples and, because samples vary, observe a range of values from 4 to 10 percent with an average of 6 percent—too low. Does that mean we should dump the crop? Uncertainty creeps in from two possible explanations for the low values. Either the crop really does have an unusually low soft resin content or, even though the *samples* contain low amounts, the full crop is actually fine. The whole point of taking random samples is to rely on them as faithful representatives of the full crop, but perhaps we were unlucky in choosing samples with uncharacteristically low levels. (We tested only nine, after all.) In other words, should we consider the low resin in our samples as significantly different from 8 percent or mere natural variation?

This problem is not unique to brewing. Rather it pervades all scientific inquiry. Suppose that in a medical trial both the treatment group and the placebo group improve, but the treatment group fares a little better. Does that provide sufficient grounds to recommend the tested medication? What if I told you that the two groups received two different placebos? Would you be tempted to conclude that the placebo given to the group with better outcomes must have medicinal properties? Or could it be that when you track a group of people, some of them will just naturally improve, sometimes by a little and sometimes by a lot? Again, this boils down to a question of statistical significance.



Shuyao Xiao

The theory underlying these perennial questions in the domain of small sample sizes wasn't developed until Guinness came on the scene—specifically, not until William Sealy Gosset, head experimental brewer at Guinness in the early 20th century, invented the *t*-test. The concept of statistical significance predated Gosset, but prior statisticians worked in the regime of large sample sizes. To appreciate why this distinction matters, we need to understand how one would determine statistical significance.

Remember, the hops samples in our scenario have an average soft resin content of 6 percent, and we want to know whether the average in the full crop in fact differs from the desired 8 percent or we just got unlucky with our sample. So we'll ask a question: What is the probability that we would observe such an extreme value (6 percent) if the full crop were typical (with an average of 8 percent)? Traditionally, if this probability, called a *P* value, is less than 5 percent, or 0.05, then we deem the deviation statistically significant, although different applications call for different thresholds.

Often two separate factors affect the *P* value: how far a sample deviates from what is expected in a population and how common big deviations are. Think of it as a tug-of-war between signal and noise. The difference between our observed mean (6 percent) and our desired one (8 percent) provides the signal—the larger this difference, the more likely the crop really does have a low soft resin content. The standard deviation among flowers brings the noise. Standard deviation measures how spread out the data are around the mean; small values indicate that the data hover near the mean, and larger values imply wider variation. If the soft resin content typically fluctuates widely across buds (that is, if it has a high standard deviation), then maybe the 6 percent average in our sample shouldn't concern us. But if flowers tend to exhibit consistency (or a low standard deviation), then 6 percent may indicate a true deviation from the desired 8 percent.

To determine a *P* value in an ideal world, we'd start by calculating the signal-to-noise ratio. The higher this ratio, the more confidence we have in the significance of our findings because a high ratio indicates that we've found a true deviation. But what counts as high signal to noise? To deem 6 percent significantly different from 8 percent, we specifically want to know when the signal-to-noise ratio is so high that it has only a 5 percent chance of occurring in a world where an 8 percent resin content is the norm. Statisticians in Gosset's time knew that if you ran an experiment many times, calculated the signal-to-noise ratio in each of those experiments and graphed the results, that plot would resemble a "standard normal distribution"—the familiar bell curve. Because the normal distribution is well understood and well documented, you can look up in a table how large the ratio must be to reach the 5 percent threshold (or any other threshold).

Gosset recognized that this approach worked only with large sample sizes; small samples of hops wouldn't guarantee that normal distribution. So he meticulously tabulated new distributions for smaller sample sizes. Now known as t distributions, these plots resemble the normal distribution in that they're bell-shaped, but the curves of the bell don't drop off as sharply. That translates to needing an even larger signal-to-noise ratio to conclude significance. His *t*-test allows us to make inferences in settings where people couldn't before.

In 2008 mathematical consultant John D. Cook mused on his blog that perhaps it should not surprise us that the *t*-test originated at a brewery as opposed to, say, a winery. Brewers demand consistency in their product, whereas vintners revel in variety. Wines have "good years," and each bottle tells a story, but you want every pour of Guinness to deliver the same trademark taste. In this case, uniformity inspired innovation.

Gosset solved many problems at the brewery with his new technique. The self-taught statistician published his *t*-test under the pseudonym "Student" because Guinness didn't want to tip off competitors to its research. Although Gosset pioneered industrial quality control and contributed loads of other ideas to quantitative research, most textbooks still call his great achievement "Student's t-test." History might have neglected his name, but he could be proud that the *t*-test is one of the most widely used statistical tools in science to this day. Perhaps his accomplishment belongs in *Guinness World Records* (the idea for which was dreamed up by Guinness's managing director in the 1950s). Cheers to that.

Jack Murtagh is a freelance math writer and puzzle creator. He writes a column on mathematical curiosities for *Scientific American* and creates daily puzzles for the Morning Brew newsletter. He holds a Ph.D. in theoretical computer science from Harvard University. Follow Jack on X @JackPMurtagh

Medicine

- **Easy-to-Use CRISPR Tests Could Change How We Diagnose COVID and Other Illnesses**
  Gene-cutting diagnostic tests could be as easy as a rapid COVID test and as accurate as PCR

Easy-to-Use CRISPR Tests Could Change How We Diagnose COVID and Other Illnesses

Gene-cutting diagnostic tests could be as easy as a rapid COVID test and as accurate as PCR

By Simon Makin

Thomas Fuchs

When COVID first hit, waiting days for laboratory results from an ultrasensitive polymerase chain reaction (PCR) test was commonplace. Faster tests usable by anyone, anywhere, later became widely available but were far less accurate. New research paves the way for a diagnostic test that's as quick and easy as a rapid COVID test and accurate as PCR technology.

Researchers had already adapted the gene-editing technology CRISPR to identify genetic material from pathogens such as the COVID-causing SARS-CoV-2 virus. But most such efforts involved boosting or "preamplifying" the amount of DNA or RNA to be measured—a step that requires special equipment and training.

A recent study in *Nature Communications* shows how CRISPR-based tests can detect SARS-CoV-2, as well as a dangerous bacterium and cancer mutations, at PCR-level sensitivity without requiring preamplification.

CRISPR uses cutting enzymes attached to RNA molecules that match a targeted genetic sequence (in this case, one from the pathogen being tested for). The RNA “guides” the enzyme to this target and then activates the enzyme to cut the sequence. But some varieties of CRISPR enzyme don’t stop there; once activated, they go on to chop any nearby single-stranded DNA (ssDNA). Researchers can exploit this action by setting their test to trigger a flash of fluorescence when ssDNA is cut, confirming that CRISPR’s target pathogen was present.

But in that setup, each target DNA or RNA molecule activates only one cutting enzyme. To boost the signal, study senior author Ewa M. Goldys, a biomedical engineer at the University of New South Wales in Sydney, and her colleagues created tiny “nanocircles” of DNA with a short, single-stranded sequence that attaches to both ends of a target sequence. When in circular form, these strands do not trigger CRISPR enzymes. But after they’re cut, they unfold into linear DNA that CRISPR detects—activating yet more enzymes in a chain reaction. “This is easy to detect even if only a few molecules of the target are present,” Goldys says.

This strategy makes CRISPR-based tests a million times more sensitive. “Removing the preamplification step allows for an elegant, simple chemistry that can be more amenable to point-of-care systems,” says Massachusetts Institute of Technology biologist Jonathan Gootenberg, who co-developed an earlier CRISPR diagnostic system. The new approach could allow for cheap test-kit components, including lateral flow strips akin to those in current rapid COVID tests—each costing a few dollars to make.

The scientists’ nanocircle-based tests detected genetic material from SARS-CoV-2 and the ulcer-causing bacterium *Helicobacter pylori*, and they were also able to find tumor DNA circulating in mouse blood and in human plasma. Such tests can work within 15 minutes, whereas PCR typically takes an hour or more. “We believe we’ve created a technology that has a realistic chance to supersede PCR,” Goldys says.

The group is collaborating with commercial partners on viral diagnosis and parasite detection in water. The first product, though, is a box of general-use nanocircles that researchers can add to existing CRISPR tests to boost sensitivity. These circles come with their own guide RNA that targets the circles’ DNA once it unfolds.

The biggest hurdle will be simultaneously sensing multiple targets. Medical applications often require this capability (usually to check that tests function correctly), but Gootenberg says it will be difficult to implement. The researchers are investigating: “We don’t know how we’re going to meet [this challenge],” Goldys says, “but we’ll try.”

Simon Makin is a freelance science journalist based in the U.K. His work has appeared in *New Scientist*, the *Economist*, *Scientific American* and *Nature*, among others. He covers the life sciences and specializes in neuroscience, psychology and mental health. Follow Makin on X (formerly Twitter) @SimonMakin

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Mental Health

- ## Teens’ Mental Health May Improve When They Help Others
  Volunteering in community programs can reduce youth depression and anxiety, researchers are beginning to learn

Teens' Mental Health May Improve When They Help Others

Volunteering in community programs can reduce youth depression and anxiety, researchers are beginning to learn

By Lydia Denworth

Jay Bendt

In college my oldest son volunteered as a Big Brother and taught computer science at local elementary and middle schools. After graduating, he said his time with those young students was one of the most rewarding parts of his college experience. According to emerging research, it might also have improved his mental health. There is already considerable evidence from studies with adults that volunteering—doing something for someone else or for one's community—benefits a person's physical and mental health and improves overall well-being. Researchers have found that the sense of mattering to those around you that volunteering provides is one important reason it is associated with psychological well-being.

Now scientists are finding similar links to both physical and mental health in children and adolescents. An early experiment found that 10th graders who volunteered in an elementary school for two months showed fewer signs of harmful inflammation and lower levels of obesity compared with students who didn't volunteer. A 2023 analysis found that among more than 50,000 children and adolescents in the National Survey of Children's Health, young people who had participated in community service or had volunteered over the previous 12 months were more likely to be in very good or excellent health and stayed calm and in control when faced with challenges, and the adolescents were less likely to be anxious, among other benefits. This improvement was in comparison with young people who did not volunteer.

Granted, those findings are only correlations. "It could be that the children who were volunteering were already in great health," says study co-leader Kevin Lanza, who is an environmental health scientist at UTHealth Houston School of Public Health.

But because of an alarming rise in mental health issues among young people, Lanza and others believe this early evidence is promising enough to pursue. A 2021 advisory from U.S. Surgeon

General Vivek Murthy warned that the proportion of young people reporting persistent feelings of sadness or hopelessness had increased by 40 percent over the previous decade, starting even before the pandemic. The number of high school students seriously considering a suicide attempt rose by 36 percent. In the first years of the pandemic, the percentage of young people with depressive and anxiety symptoms doubled. There are multiple possible causes in addition to the pandemic, experts say, including the polarized political environment, anxiety over climate change, the effects of social media use and adverse personal circumstances.

When looking for ways to counter these problems, researchers point to the importance of “contribution”—providing support or resources to others or helping to achieve a shared goal—as an essential piece of social and emotional development for adolescents. Young people have a developmental need to connect and belong. “Part of the exploration of adolescence and young adulthood is figuring out where you can be needed and useful—arguably core aspects of our mental health,” says developmental psychologist Andrew Fuligni, co-executive director of the Center for the Developing Adolescent at the University of California, Los Angeles.

Volunteering is one good way young people can contribute. The importance of mattering to others and to the larger world “translates really well to the needs of adolescents to have a meaningful role to play in their community,” says developmental psychologist Parissa Ballard of the Wake Forest University School of Medicine. In a small 2022 pilot study, Ballard and her colleagues tested volunteering as an intervention for nine 14- to 20-year-olds who had been recently diagnosed with mild to moderate depression or anxiety and were recruited through their clinicians. After 30 hours of volunteer work at animal shelters, food banks, and other community organizations, the average reduction in depressive symptoms among participants was 19 percent.

Everyone in the study enjoyed the work and reported a sense of pride and accomplishment. “Young people who were struggling with anxiety said that they were pretty anxious before doing it but then felt so much better after,” Ballard says. Although volunteering should not replace mental health treatment, she says, it could help in conjunction with other forms of therapy. She is pursuing that hypothesis in a larger study.

What accounts for the benefits? Helping others improves mood and raises self-esteem. It provides fertile ground for building social connections. It also shifts people’s focus away from negative things and can change how they see themselves. Many teens say they don’t feel important, Ballard says. “Volunteering can give people a different sense of themselves, a sense of confidence and efficacy.” Lanza thinks of it as “a health pipeline.” He adds that “it equips you with certain types of skills that better control anxiety.”

There may be a potential downside to volunteering, however. Fuligni and his colleagues have found that young people’s mental health can suffer if they feel their contributions are devalued because of their gender, racial or ethnic identity. And if they feel like they are being forced to participate or are not doing much, the experience can be harmful, Ballard says. One report found that people who were required to volunteer when they were young were less likely to do such work when they were older. “Young people have to choose something that feels meaningful to them,” Ballard says. Adults can help by offering choices and by vetting volunteer opportunities to be sure that organizations are well run and equipped to offer a good experience.

When these situations are carefully thought out, volunteering doesn’t just help the volunteers. It also helps the people and communities on the receiving end. “Volunteering could be a win-win,” Lanza says.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

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

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Multiverse

- **Here’s Why We Might Live in a Multiverse**
  Several branches of modern physics, including quantum theory and cosmology, suggest our universe may be just one of many

Here’s Why We Might Live in a Multiverse

Several branches of modern physics, including quantum theory and cosmology, suggest our universe may be just one of many

By Sarah Scoles

Shideh Ghandeharizadeh

Humans live in a universe; that is a fact. Up for debate, though, is whether that universe lives in a sea of other universes—a multiverse.

The idea of a multiverse is the subject of much science fiction—but it’s also a real possibility (or rather a set of many possibilities) that some scientists take seriously and investigate.

Multiversal concepts pop up in several branches of modern physics. In quantum mechanics, for instance, a particle exists in a superposition of all possible states at once—until, that is, someone tries to make a measurement of it. At that point, the possibilities collapse, and one physical state becomes apparent to the observer. The “many worlds” interpretation of quantum mechanics, though, posits that all the possible states the measurement might have shown play out in different universes, each with a different version of the observer.

The many-worlds interpretation is perhaps the most famous scientific idea of a multiverse. But it’s far from the only one. In his new book, *The Allure of the Multiverse: Extra Dimensions, Other Worlds, and Parallel Universes*, physicist Paul Halpern of Saint Joseph’s University in Philadelphia explores these potential parallel realities, along with their histories and evolutions, their philosophies and the insights they offer into the nature of science.

Scientific American spoke to Halpern about how the concept of the multiverse fits with modern physics, the evidence scientists have for it so far, and what it all means for the nature of our existence.

An edited transcript of the interview follows.

What exactly is a multiverse, anyway?

There are different ideas about the multiverse: cultural ideas and scientific ideas. Those notions tend to be very different. The cultural ideas apply to human life. People wonder what would have happened if they had moved to a different city, taken a different job, decided to pursue different hobbies or had a different relationship. They imagine paths they didn’t take and try to picture what would happen.

In science, the idea can be split into the quantum multiverse and the cosmological multiverse. The quantum multiverse is a possible answer to the questions of what happens when measurements are taken in quantum physics and how human life is connected to the quantum world. That was addressed in 1957 by a young graduate student, Hugh Everett III, with the many-worlds interpretation. He speculated that different possibilities split into different universes—and that humans experience multiple realities but don't really know about their doppelgängers.

And there's the cosmological multiverse, which is the idea that a process called inflation, the rapid expansion believed to be an early stage of the universe, is relatively easy to achieve in the early universe and elsewhere and happens all the time. It results in other bubble universes that expand, and our universe has also expanded, so they're currently beyond our scope.

What are the properties of this universe that make physicists think a multiverse might be a correct interpretation of reality?

The parameters of our universe seem to be within the right range for galaxies, stars, planets and life to form. If these constants—the strength of gravitation, the strength of the electromagnetic interactions, and so forth—were adjusted just a bit, then planets and life as we know it never would have formed. This is sometimes called the fine-tuning problem.

One reason for this fine-tuning was proposed by physicist Brandon Carter around 1970. He suggested that maybe something about our enclave of the universe, and maybe even our whole universe, is special. Maybe, then, we should think about all the other possibilities and consider why we're in this branch of the universe rather than the others. And that might have something to do with the fact that there's an array of possible universes, and we happen to be one of the few that could support structure formation and eventually lead to life as we know it. But in most of the other versions, we would not be here.

One problem with those other universes is that, if they exist, they're beyond our perception. Scientists don't currently have a way to directly test the idea of the multiverse. In your book, you lay out some ideas for indirect tests and note that in the future we might come up with clever direct experiments. But what does it mean that the multiverse is currently untestable?

There are other ideas in physics now that can never be tested directly. For example, the universe is expanding and accelerating, and light has a finite speed, so we're never going to be able to see parts of the universe that are beyond a certain radius. Beyond roughly 46 billion light-years we can only use our imagination. But it could be that nature has surprises beyond the range of observability, and we would never know.

Quantum uncertainty also limits what we can observe at once. Because of Heisenberg's uncertainty principle, we couldn't, even in theory, plot out the positions and momenta of all the particles in the universe at once.

The fact is that physics has evolved to a point where there are a lot of things that are not directly measurable. If we can come up with a theory that explains everything within the observable universe, and it requires reference to a multiverse, there is a segment of scientists who would say, "Well, we need to accept that there will be things that we will never know." There are others who stubbornly might pursue other possibilities.

I think everyone would agree that if we could come up with a theory of the universe that is self-consistent, is all-encompassing and doesn't rely on unobservable things, then that would even be better, but it might not happen.

Some researchers say that if something is untestable in traditional ways, it's not science—it's pseudoscience. To you, is the goal of science to try to find the truth of the universe or simply to find things that can be proved through experimentation?

Humanity has an ambition to try to understand everything in its world, and that now has become everything in its universe. We're a very bold group of people living on a planet that's a relatively tiny part of everything. We use our instruments to try to understand it as much as we can. We use different tools, and one of those tools is theoretical physics; another tool is direct observation. We hope that those methods match up, but sometimes there's a lag. Sometimes there are experimental results that theory does not explain. Sometimes there are theoretical models—such as general relativity—that seem so compelling that there's some degree of acceptance without observation, and only later does science produce experimental results.

There are exciting ideas in theory that take a little while to test, so one has to be patient. But, of course, if a better theory comes along that matches experimental tests, then people are going to flock to the better theory. They're not going to always wait for the original theory to be confirmed.

Do you think most physicists are open to the idea of a multiverse?

When I was interviewing different people, I had some surprises. Some people whom I thought were very observation-based, hard-headed scientists turned out to be very open to the idea of a multiverse. And then others who have their own, maybe far-reaching, ideas turned out to be drawing the line, saying, "No, we can't have a multiverse, but we can have these other things."

Different theorists have their own tastes. The limits for one researcher might be completely different than the limits for another researcher. There’s a certain amount of personal philosophy involved.

I guess people are always people, with their own preferences, even in the sciences.

Even if you’re a trained physicist and are basing everything on laws of physics and things like general relativity and quantum physics, there’s always some room for philosophical preferences. There are some physicists who really like to think that time is an illusion, and others like to think that time is real. That verges on philosophy because it’s hard for us, or even impossible, to step outside of time and say, ‘Hey, wait a minute, it was an illusion all along. Really, the world is timeless.’ We can’t really do that. So we can only kind of speculate about whether time is really passing physically or whether, in reality, time and space are on the same footing and we’re just inside some kind of illusory realm in which time passes in our own minds.

Is there an overarching idea that you hope *The Allure of the Multiverse* conveys?

I’d like people to appreciate the range of possibilities in theoretical physics—even of things that are well accepted, such as the general theory of relativity and quantum physics—and understand that it is a great mystery how all these possibilities somehow filtered down into the universe that we observe today. It’s a mystery why things are the way they are, given all of the options.

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

Neuroscience

- **My Synesthesia Transforms Speech into Text I ‘See’ in My Head**
  From the time I learned to read, I have experienced a form of mental closed-captioning called ticker-tape synesthesia

My Synesthesia Transforms Speech into Text I ‘See’ in My Head

From the time I learned to read, I have experienced a form of mental closed-captioning called ticker-tape synesthesia

By Emily Makowski

Cinta Fosch

I spend my days surrounded by thousands of written words, and sometimes I feel as though there’s no escape. That may not seem particularly unusual. Plenty of people have similar feelings. But no, I’m not just talking about my job as a copy editor here at *Scientific American*, where I edit and fact-check an endless stream of science writing. This constant flow of text is all in my head. My brain automatically transcribes spoken words into written ones in my mind’s eye. I “see” subtitles that I can’t turn off whenever I talk or hear someone else talking. This same speech-to-text conversion even happens for the inner dialogue of my thoughts.

This mental closed-captioning has accompanied me since late toddlerhood, almost as far back as my earliest childhood memories. And for a long time, I thought that everyone could “read” spoken words in their head the way I do.

What I experience goes by the name of ticker-tape synesthesia. It is not a medical condition—it’s just a distinctive way of perceiving the surrounding world that relatively few people share.

Not much is known about the neurophysiology or psychology of this phenomenon, sometimes called ticker taping, even though a reference to it first appeared in the scientific literature in the late 19th century.

Ticker taping and other forms of synesthesia are experiences in which the brain reroutes one kind of incoming sensory information so that it is processed as another. For example, sounds might be perceived as touch, allowing the affected person to “feel” them as tactile sensations.

As synesthesias go, ticker taping is fairly uncommon. “There are varieties of synesthesia that have just been completely under the radar—and ticker tape is really one of those,” says Mark Price, a cognitive psychologist at the University of Bergen in Norway. The name “ticker-tape synesthesia” itself evokes the concept’s late 19th-century origins. At that time stock prices transmitted by telegraph were printed on long paper strips, which would be torn into tiny bits and thrown from building windows during parades.

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Ticker-tape synesthesia is so obscure that some synesthesia researchers, including Price, became aware of it only after coming across anecdotal reports. Price likens synesthesia research in general to “exploring a new universe: you just sort of stumble across these planets you didn’t even know existed,” he says.

Only recently have a few scientists finally begun to study ticker taping in earnest. Their interest has been generated by a desire to learn about the neural connections that make up the brain’s reading networks. Such efforts might help us better understand dyslexia, a neurodevelopmental condition that makes reading and writing difficult.

These studies are expanding the ranks of ticker tapers. Many people with ticker-tape synesthesia realize that they have it only after they learn about the phenomenon from researchers who are recruiting participants for studies. This growing awareness just reiterates the vast range of human experience. “You never know if your perception is a normal perception or if it’s a particular perception that differs from other ones,” says Fabien Hauw, a neurologist and cognitive neuroscientist at the Paris Brain Institute, who has studied ticker taping.

I recognized my own synesthesia for the first time when I was in my mid-20s. During a conversation, I saw one word in my head spelled in Internet slang—I think it was “gr8” instead of “great.” When I mentioned it out loud, I learned that other people didn’t perceive words this way. Like many people with synesthesia, I had assumed that everyone else shared my experience, and I hadn't realized that there was anything unusual about it—it was just part of my everyday perception of the world around me. This "is often the case with synesthesia, I believe, because it has no real consequence," says Laurent Cohen, a neurologist and cognitive neuroscientist at the Paris Brain Institute and Hauw's former Ph.D. adviser. "It's not an impairment; it's not a disease."

Hauw, Cohen and their colleagues have published several recent studies on the experiences of being a ticker taper. In one, they researched the potential benefits and drawbacks of ticker taping in 22 individuals. The researchers found that ticker tapers were faster and generally more accurate in three tasks involving spoken words than control participants who lacked this mental word-streaming ability. The tasks involved counting the number of letters in words, spelling them backward and deciding whether they contained letters written with an "ascending" stroke (such as b or d) or a "descending" one (such as p or q).

In two other experiments, the participants had to ignore background speech. In one experiment, they decided whether visually presented terms were actual words or pseudowords. In the other, they pressed a button based on which of two letters they had seen. Surprisingly, the audio of spoken words did not hinder most of the ticker tapers from performing these tasks. Although ticker tapers have self-reported difficulty reading when surrounded by people who are talking, they might also become used to the words they constantly perceive and learn to tune those words out to some extent. "They are probably highly trained at focusing their attention," Cohen says.

In another study, the same researchers looked at how a separate group of 26 ticker tapers perceived words and found a great deal of variation. Most were "associators"; they visualized the words internally or perceived the words as located behind their eyes, which is roughly how I would describe my own experience. I don't literally see words in front of me; instead I automatically visualize them in my mind, and if I hear two conversations at once, I see snippets of both in different “areas” of the visual field of my mind’s eye. I see maybe three or four words at a time, and I “read” them in my head. (In contrast, some other ticker tapers have reported that they see words scroll by.)

In Cohen and Hauw’s study of 26 ticker tapers, a smaller subset of the participants saw words projected onto the external visual scene, appearing, for instance, near a speaker’s mouth—almost like a speech bubble in a comic. For some, the word stream appeared at the bottom of their visual field like film subtitles. Differences also were noted in the words’ visual attributes and movement in space and in the number of words that appeared at one time. “There was a lot of variability depending on the stimuli and the circumstances,” Hauw says.

> It’s nice to see that enough of us are out there to spur a growing amount of research into ticker-tape synesthesia.

Price and his colleagues have also studied the variety of ticker-tape experiences. They surveyed 425 people in Norway—some with ticker-tape synesthesia and some without it—and estimated that only about 0.6 to 3.2 percent of the participants had obligatory ticker taping, meaning that they automatically saw all the words that they heard, spoke or thought. Other people reported that they involuntarily perceived the stream of words only occasionally, and some even were able to call up the mental text voluntarily. Further, some participants saw the closed-captioning only for their own thoughts, not for spoken words. “Weaker tickertapers form part of a graded continuity of experience,” the authors wrote. “This extends from obligatory tickertaping ... to the kind of vague visualization of short single words that probably most of us can conjure in our mind with some effort.” In that study, ticker tapers did not self-report that they were skilled at backward spelling or letter counting, but “it could be that people who had ticker taping didn’t know that they have those skills,” Price says.

I had never really thought about ticker taping’s potential advantages and downsides before I read these studies, which raised a whole series of questions. Did my synesthesia help me win a spelling bee in school as a kid? Is it a reason I always scored so high on word-memorization quizzes? Maybe ticker taping helped mentally reinforce my studies, especially because I subtitle my own thoughts. Yet I still get hung up on spelling certain words, such as “committee” or “embarrassed” or “vacuum.” And when I see them in my head, they always look fuzzy. As far as the negatives of ticker taping are concerned, I find it hard to tune out other people’s conversations, especially in an open-office setting, because the ticker tape of their dialogue pops up in my mind.

But it doesn’t distract me to the point where I find myself reaching for my headphones all the time either. Like the participants in Hauw and Cohen’s study of 22 ticker tapers, I can concentrate on a task even with my subtitles popping in and out in the background in the same way that a person watching a movie can sometimes ignore subtitles in a language they speak. The subtitles are such an intrinsic part of how I perceive the world that it’s hard for me to imagine life any other way.

Because ticker taping involves spoken words inducing images of written ones, there is some debate over whether it is really a form of synesthesia at all. Synesthesia typically involves wiring one sensory input to a very different one, such as a connection between sound and touch. Ticker taping, in contrast, appears to exist entirely within the realm of language processing. Spoken and visualized words go together in a way that smells and sounds or tastes and colors do not.

For most of human history, most people were illiterate, so ticker taping is a relatively new phenomenon. Jamie Ward, a professor of cognitive neuroscience at the University of Sussex in England, says that same objection could be raised for other types of synesthesia that have been better studied, though. Imagine, he says, that a person with grapheme-color synesthesia—someone who associates particular letters with different colors—has never seen a letter that triggers it in their life. Do they still have synesthesia? “I would say that actually [their] brain is wired differently” from unaffected people’s, he says. “People with synesthesia think and act in a way that is coherent unto themselves.”

Ward has studied synesthesia clustering—the relationships among different types of synesthesia based on how likely they are to show up in the same individual. In a study he co-authored, ticker taping was one of several more prevalent forms of synesthesia that didn’t cluster with any other type. Part of the reason for this, however, may be that the study split up synesthesia into 164 subtypes that were used for grouping these relationships. Seeing colored letters clustered with seeing colored numbers, for example, but both these experiences can be categorized as grapheme-color synesthesia.

Ward says ticker taping did have associations with other types of synesthesia, although these associations weren’t as strong as the ones that some other types of synesthesia have with one another. In general, however, “the more types of synesthesia you have, the more likely you are to develop another kind of synesthesia,” Ward says. “It’s almost as if the brain develops synesthesia but not just once. It can develop over and over again.” In Cohen and Hauw’s study of 26 ticker tapers, 69 percent reported that they had at least one other type of synesthesia. (I personally associate a few letters of the alphabet and days of the week with colors but not all of them. Although those pairings are always present, they don’t seem as vivid to me as my subtitles.)

Functional magnetic resonance imaging (fMRI) studies performed by Cohen, Hauw and their colleagues are starting to provide insight into ticker taping’s neurological basis. In a case study of a single individual with ticker-tape synesthesia, the researchers found that, when listening to speech, certain areas of the brain’s left hemisphere were more active in the ticker taper than they were in control participants.

These areas included the inferior frontal gyrus, the supplemental motor area, the supramarginal gyrus and the precuneus, which are all involved in speech processing. Also included was the visual word-form area, a region of the cortex thought to be involved in identifying written words and letters. When the researchers had the ticker taper read written words, the same brain areas encompassing both speech and text processing were activated. In other words, the individual’s reading network seemed to be overactivated when listening to speech.

The researchers suggest that ticker taping might result from atypical development involving hyperconnectivity between brain areas for speech and vision when people learn to read. Another fMRI study co-authored by Cohen and Hauw that was recently published shows similar findings of brain overactivation in 17 ticker tapers.

Further suggestive evidence comes from studies on dyslexia that demonstrate reduced connectivity in these brain areas. Cohen and Hauw have posited that ticker taping could be considered the opposite of dyslexia, although Cohen cautions that this hypothesis may be simplistic. “Dyslexia is a very diverse set of conditions, and possibly ticker-tape synesthesia may also be relatively diverse,” he says. “I’m not sure to what extent it’s exactly accurate to present both conditions along a single continuum, but that’s the idea.”

“It’s really just speculation because we have not compared both groups,” Hauw says. He notes that more studies are needed to compare the brain activity of ticker tapers with people with dyslexia, allowing researchers to learn more about both conditions.

“It can help us to have a better understanding of how the brain works and how different regions are connected,” Hauw adds.

There’s likely an environmental component to ticker taping as well. In Hauw and Cohen’s study of 26 ticker tapers, 77 percent recalled having been avid readers during childhood, and the majority said that they read a lot in adulthood. In my case, both my parents worked as librarians at one point, and my childhood home was always filled with books. My parents read to me every day when I was a child, and I learned to read at a very young age. Also, in one of my few memories from before I learned how to read, I’m imitating my mom’s perfect cursive by scribbling on a piece of paper. It’s possible that the environment I grew up in inadvertently encouraged the development of my synesthesia.

In addition to learning more about the brain’s reading network, I’ve come to better understand myself and other ticker tapers through these studies. None of the researchers that I spoke with for this article have this form of synesthesia themselves, and I still haven’t met someone else with it in person—that I know of, at least. But it’s nice to see that enough of us are out there to spur a growing amount of research. This work sets its sights beyond solely studying the seeming quirkiness of ticker taping. Insights about how the brain processes words could illuminate a vast continuum of human experience.

Are you a scientist who specializes in neuroscience, cognitive science or psychology? And have you read a recent peer-reviewed paper that you would like to write about for Mind Matters? Please send suggestions to Scientific American*’s Mind Matters editor Daisy Yuhas at* dyuhas@sciam.com.

This is an opinion and analysis article, and the views expressed by the author or authors are not necessarily those of Scientific American.

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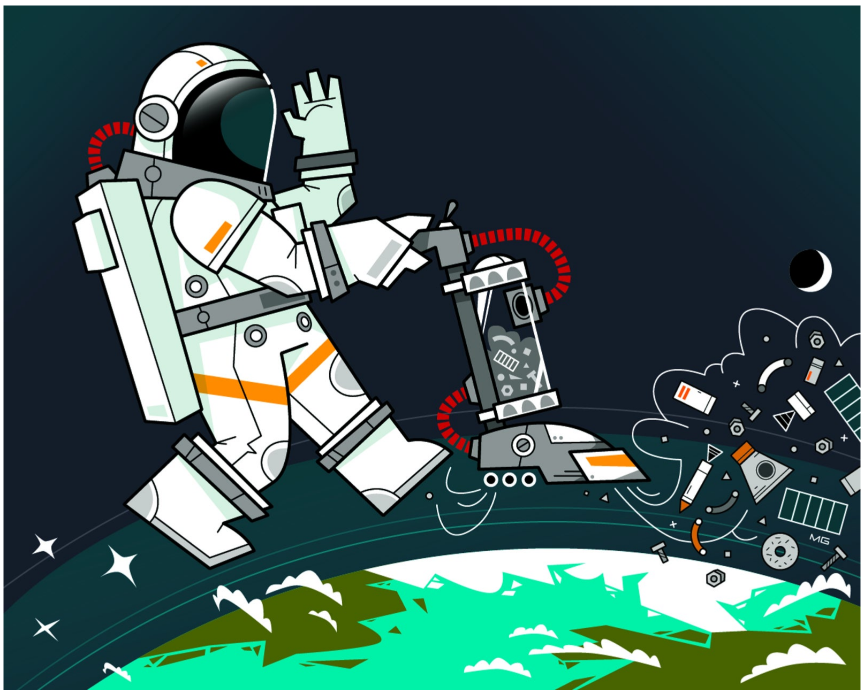
Space Exploration

- ## Space Trash Threatens the Global Economy
  Without global regulations to mandate the cleanup of Earth’s orbit, debris from defunct spacecraft and collisions threatens the burgeoning space economy

Space Trash Threatens the Global Economy

Without global regulations to mandate the cleanup of Earth’s orbit, debris from defunct spacecraft and collisions threatens the burgeoning space economy

By The Editors



Martin Gee

Space should not be a garbage dump. Nevertheless, we have treated the sky as a wrecker’s yard for more than half a century, and the amount of space junk orbiting Earth has skyrocketed in recent years. Now filled with the decaying hulks of defunct rockets and satellites, our polluted orbital environment is becoming more crowded by the day, threatening the growing space economy. It’s time for nations—and the billionaires commoditizing space—to clean up Earth’s near orbit.

The U.S. Air Force tracks more than 25,000 pieces of space junk larger than 10 centimeters—about the size of a bagel—weighing together some 9,000 metric tons. This dangerous trash zips around

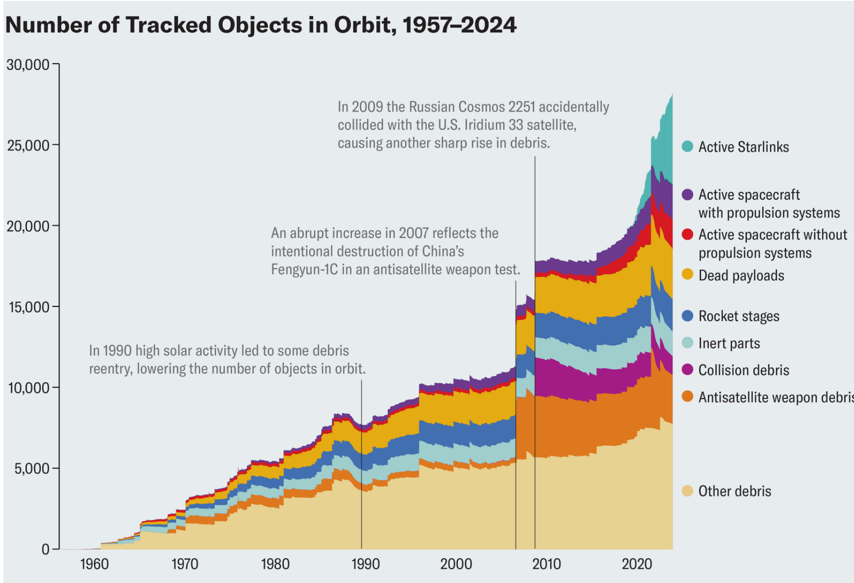
Earth at speeds of roughly 10 kilometers per second, or more than 22,000 miles per hour. Collisions between millimeter-scale objects too small to track and working satellites are now routine, as are near-miss disasters. One example is a NASA research satellite that almost hit a defunct Russian satellite in February. Orbital debris collisions cost satellite operators an estimated $86 million to $103 million in losses a year, a figure that will grow as each operator and each collision generate more debris.

The threat isn't just in space. In March part of a pallet from a discarded International Space Station battery fell to Earth, smashing through the roof of a Florida home. In 2020 an Ivory Coast village recovered a 12-meter-long pipe from space, courtesy of a Chinese rocket that cast off its empty core after launch. And a 2022 *Nature Astronomy* study puts the odds of space junk killing someone on the ground at 10 percent every decade. Needlessly.

Under the 1967 Outer Space Treaty, nations are supposed to be responsible for damages caused by space junk, even if it was originally launched by a private firm. That puts taxpayers, not space-exploring billionaires, on the hook for damages from orbital debris if its origin can be proved and the company shown negligent—a tough proposition for untraceable paint chips. No surprise, this hasn't worked. The problem is, after decades of discussion, there is still no international treaty that limits space junk or sets standards for negligence. We need one that outlines responsibilities and imposes fines on the companies whose spacecraft debris causes harm.

As long as doing the right thing is voluntary, it may not happen, concluded a 2018 Air Force Association report. The limited action since then tells us the world is way overdue for an agreement on mandatory standards. Few countries or companies currently design rockets for their complete life cycle. They must be forced to store enough fuel and retain the capability for spacecraft to steer safely out of space when their useful life is over. Painful financial and regulatory penalties should afflict spacefaring industries and nations that fail to play by the new rules.

Why? Because the physics of orbital debris spells doom. Between 775 and 975 kilometers overhead, derelict satellites pass within 1,000 meters of one another 1,000 times a year. Any collision would instantly double the amount of trackable debris in orbit and create countless smaller, yet still dangerous, bits of space junk to rain down on valuable satellites below them. The 2013 film *Gravity*, about astronauts lost in space after orbital debris destroyed their space shuttle, was fictional, but the threat of a cascade of space debris is real. This is the so-called Kessler syndrome, where smashups produce so much garbage that Earth's orbit becomes untenable. A 2023 study predicted that low-Earth orbit can hold only about 72,000 satellites without serious risk of this catastrophe occurring.



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

We are far closer to that red line than many people realize. There is a land rush happening right over our heads, in space. And it is coming from private companies, not national governments. There are almost 10,000 satellites in orbit right now, up from 6,500 only three years ago. The nearly 6,000 Starlink satellites launched by Elon Musk's SpaceX now make up more than half of the total, and they are part of a planned fleet of up to 42,000. Starlink is only the first of at least six more such "mega-constellations" underway or in the offing.

SpaceX and its rocket industry competitors plan to further fill space as we move into the new space economy. The jumbo Starship rocket Musk is testing right now in Texas promises to be able to carry six times more satellites to orbit than its predecessor, the workhorse Falcon 9 rocket, at a lower cost per pound. The economy of the 21st century will run on the ubiquitous fleets of satellites delivered by these kinds of rockets, providing communications, transactions, observations, and much else. Unless we wreck the sky.

Satellite slots are now allocated by the International Telecommunications Union (ITU), based in Geneva, as well as individual nations’ rules. The ITU largely concerns itself with ensuring that satellite radio-frequency assignments don’t interfere with one another. The agency doesn’t even check that satellites are actually in their promised orbits, to address collision concerns. In 2020 the Inter-Agency Space Debris Coordination Committee, governed by 13 space agencies, including the U.S., Russian and Chinese ones, released guidelines for limiting space debris. They called for deorbiting satellites—burning them back to Earth or retrieving them—within 25 years, which the Federal Aviation Administration made a rule for U.S. launches only last year. This is an overdue but good start from the U.S.

Although commerce might be the bulk source of space debris, the militarization of space has had and will continue to play a role in cluttering orbits. We need a global treaty along the lines of the Antarctic convention to keep space clean before tensions rise any further. This could be led by the United Nations Committee on the Peaceful Uses of Outer Space. In 2023 NASA proposed a comprehensive plan to remove derelict hulks in orbit and smaller debris. We should fund that endeavor as a mission of the civilian space agency, starting with deorbiting U.S. derelicts. The mission would be a boon to the growing U.S. space industry, as if common sense didn’t offer reason enough.

Along those economic lines, even without a Kessler syndrome cascade, economists estimate space debris will cost nearly 1 percent of global gross domestic product in losses every year by the next century, the one wherein a Kessler cascade will almost certainly take place if we aren’t careful. That might not sound like a lot, but that penny tax would represent a trillion-dollar cost to humanity—an unnecessary one, even by the size of today’s world economy.

The laws governing satellite orbits and operations were written during the cold war in the mid to late 20th century, at a time when only a few governments operated only a few satellites. We live in a new era of private space exploration, one that is more extractive and invasive than before, with many nations and companies participating. We need better rules to keep us from trashing Earth's orbit as badly as we have trashed Earth itself.
