

NAUTILUS

ARE WE SMARTER THAN PLANTS?

Intelligence gets a new definition

THE GEOLOGISTS KNOW

As Antarctica goes, so goes our fate

YOUR BRAIN'S MYSTERY TOUR

The shaky neuroscience of psychedelics



The Awe Effect

WHAT POWERS SCIENCE p.22



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CONTACT

360 W 36th Street, 7S
New York, NY 10018

info@nautil.us

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The Most Beautiful Thing

BY KATHERINE HARMON COURAGE

HOW DO WE CHANGE not just our mind, but our perspective? It's not a small question. And not an insignificant one right now. In this issue of *Nautilus*, we have some unexpected answers.

Our cover story, by notable evolutionary molecular biologist Sean B. Carroll, takes us on a journey of his own scientific discovery. Not in his own research, but in wanting to know what so moved people about a movie scene showing a potentially revolting mischief of rats. His investigation led him deep into the growing scientific study of awe and wonder.

These feelings are not just nice-to-haves. It turns out they are “the prime emotions that spark and sustain scientific exploration, discovery, and creativity, that motivate science learning, and” (crucially, I’ll editorialize) “that inspire the public’s interest in science and nature,” he writes. Fortunately, awe can be found not just at singular wonders like the Kakombe Waterfall. But, as Carroll discovers, in the very stories we tell. In experiences—increasingly rare perhaps—of “being pulled out of ourselves.”

Another avenue for changing perspectives is of course to dive deeper into ourselves. As neuroscientist Grigori Guitche discovers when he takes a psychedelic for the first time, the mind is even more mysterious than we thought. In talking with researchers

afterward, he uncovers that the science isn’t exactly clear on why these drugs seem to be so broadly helpful for treating many different clinical conditions and for shifting entrenched perspectives.

There may be few harder perspectives to shake than that of exceptionalism. And humans are the worst offenders. But in a 16th-century chapel, a motley crew of minds—an astrophysicist, cosmologist, ecologist, essayist, Indigenous scholar, philosopher, and neuroscientist—assembled recently to see what might be done about this. Specifically, how we might entirely remodel our idea of what intelligence really is and what it truly could be. It turns out, our correspondent at this unconventional gathering (science writer Amanda Geffer) reports, we might have a lot to learn from trees.

In this issue, we also offer new perspectives on the importance of Antarctica’s bedrock, the “unknowability” of birds, what it’s like to work at the bottom of the sea, and whether the evolution of an intelligent life form—capable of asking vexingly difficult questions—was all that unlikely after all. And we’re so grateful to be able to bring you these rare and surprising stories.

Because, in the words of Albert Einstein (elegantly selected by Carroll): “The most beautiful thing we can experience is the mysterious. It is the source of all true art and science.”

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PLUS

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and the joy of sticks

SEA BEYOND

From the ocean we have to the ocean we want

Sea Beyond is the educational programme promoted by the Prada Group and UNESCO's Intergovernmental Oceanographic Commission (IOC), to raise awareness on sustainability and ocean preservation. The programme recently extended its scope beyond education, with two new areas of focus related to the ocean: support for scientific research and humanitarian projects. Sea Beyond is funded by 1% of Prada Re-Nylon collection revenues.

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2021 United Nations Decade
of Ocean Science
2030 for Sustainable Development

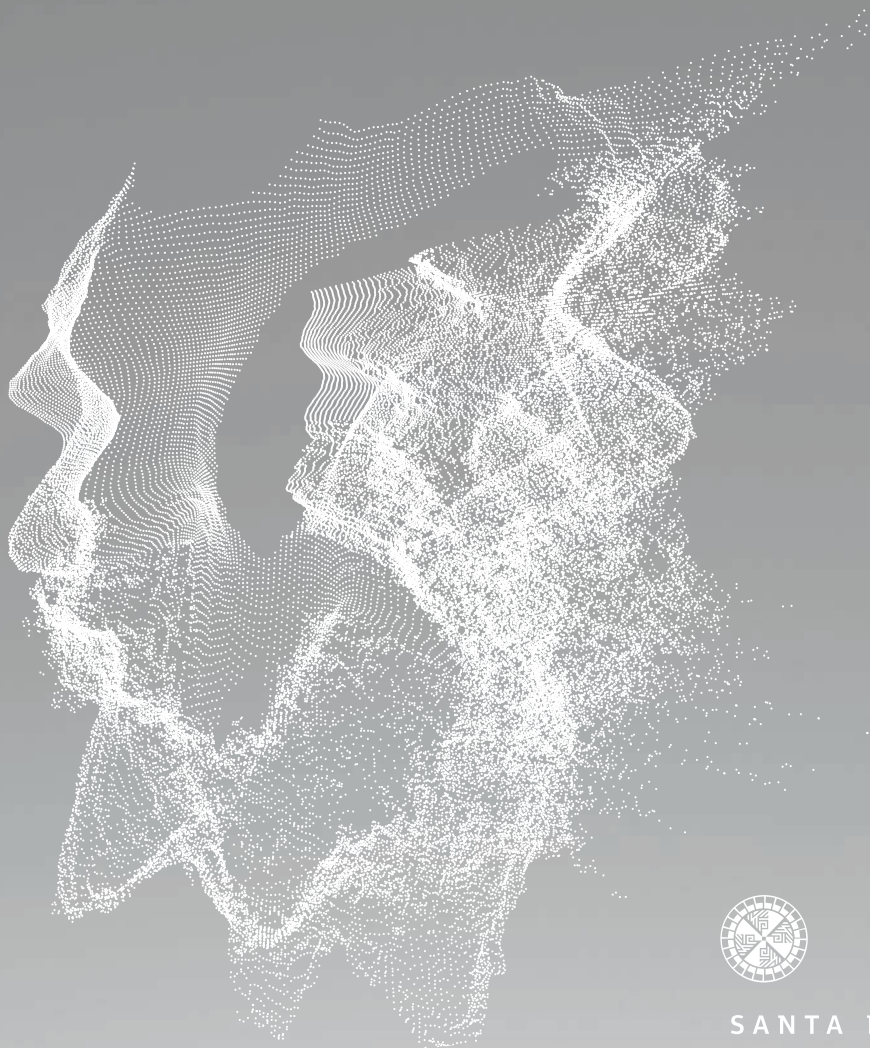
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THE PORTHOLE

Short sharp looks at science

PSYCHOLOGY

People Really Want to Be Good

AN OLD PHILOSOPHICAL chestnut concerns the question of what motivates acts of altruism: selflessness or self-interest. Some argue that humans are most likely to help others in contexts where their actions also indirectly benefit themselves or their kin and loved ones.

Scientists have mostly attempted to resolve this conundrum by observing behavior and have found that while people do act in the interests of others, they are less likely to do so when they are dealing with members of outgroups, and will often cheat strangers in economic games.

Recently, however, a team of scientists approached the question of what guides altruism from the perspective of motivation. The team, including Kyle Law, a post-doctoral researcher at Arizona State University, and Ph.D. student Seoyeon Bae from Boston College, studied anonymous survey responses from almost 1 million individuals spread over more than 100 countries, taking into account different cultural contexts, age ranges, socioeconomic levels, and time periods. They found that the vast majority reported performing acts of altruism because they were interested in the well-being of others, not because these acts benefitted them indirectly.



“People are more likely to want to be remembered for making a difference, helping others, and improving the world,” says Bae, “and to value things like caring over status or personal gains.”

The scientists assessed motivations for acts of altruism along three different dimensions: legacy (how they wish to be remembered), life aspirations, and basic human values. They used different datasets for each dimension. For their analysis of legacy motivations, they conducted secondary analyses on data from 8,000 individuals across 22 previously collected samples from world populations. Their analysis suggested that when



People are more likely to value things like caring over status or personal gains.

thinking about what kind of legacy they want to leave, people are significantly more likely to report being motivated by making a positive impact on the world than by strengthening their reputations. “That shocked me,” said Law.

To identify how life aspirations shape motivations to perform altruistic acts they analyzed responses from 59 study samples across 22 countries collected over two decades. In this analysis, they found people were much more likely to report being motivated by values such as personal growth and community giving than by values such as wealth or fame. In the final analysis, which examined how basic human values shape altruistic motivations, they used three large-scale global datasets—one of undergraduate students, another of primarily European adults, and a third of individuals from a more geographically diverse set of 78 countries—and found that values such as universalism and benevolence were more common reported motivators of altruism than values such as power, hedonism, and achievement. They also found that more individualistic countries, such as the United States, actually scored higher on other-oriented motivations than more communal ones such as Japan, a surprising finding, as individualistic cultures are often thought to be more selfish.

Trying to understand why people act the way they do by simply asking them to explain their behavior is generally viewed with skepticism by psychology researchers, and for good reason. We often don’t know why we act

the way we do, and will make up a reason on the spot without realizing it, and that reason may be self-serving. Psychologists call this “confabulation.” Another possibly larger problem is the “social desirability bias”—people will often tell researchers what they think they want to hear or what they think will impress the experimenter.

This study relied on self-report, which is prone to both biases. However, people present less of this bias in anonymous surveys like the ones used here. Further, the survey respondents the scientists analyzed included populations of identifiable altruists: people who donate organs to strangers and others who belong to the effective altruist movement, which is focused on finding the most efficient way of helping the maximum number of people in the world. If the average survey respondent was just trying to look good, rather than reflecting honestly on their motivations, we might expect them to score similarly to the organ donors, the researchers reasoned. But they didn’t. The effective altruists and organ donors had much higher scores on altruistic motivations.

“We did expect some difference, but the magnitude was really striking, and it drove home for us the idea that these aren’t just people that behave differently,” Law said. “They seem to think differently, value different things, and prioritize helping others at a deep motivational level. And it also made the results feel more real to us and more grounded, not just survey noise or social desirability, but a reflection of something that’s more meaningful and possibly enduring.”

We should take care not to assume people are always selfish. That’s a bias, too. Human motivations are difficult to discern. Studies show that when observing others perform acts of altruism, we tend to assume they are doing so to benefit their reputations, but we don’t apply this bias to ourselves.

“The study matters because our assumptions related to human nature shape everything,” Bae says. “If we assume people are primarily self-interested, we would design systems around incentives, competition, or punishment. But if people are motivated by concern for others, we can build systems that nurture and amplify those motivations in a very positive way.”

Of course, motivation does not always lead to action. But there is a comfort in knowing that the motivation to be good is there. We just need to learn how to tap into it.

—Jim Davies



ASTRONOMY

Eye of Sauron Hints at Cosmic Mystery

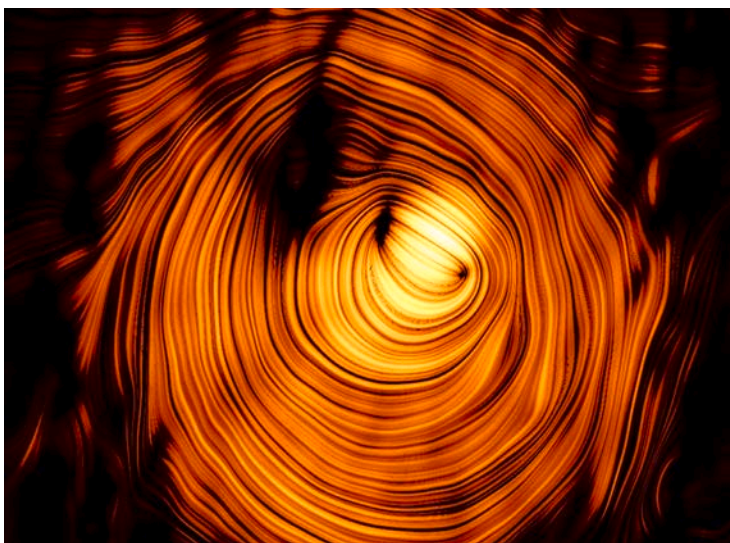
A NEW ASTRONOMICAL IMAGE shows a one-of-a-kind deep space object that seems to peer down at us on Earth like the Eye of Sauron, portrayed as a flaming eye in *The Lord of the Rings* movies. That object, shown here, is called a blazar, a jet of radiation issuing from a supermassive black hole, and it is shining deep in the heart of an active galaxy 3.5 billion light-years away.

Also known as PKS 1424+240, this blazar happens to be one of the brightest in the sky. It has puzzled astronomers since it was discovered in the 1970s. Though its jet appears to move sluggishly, it also seems to be one of the biggest emitters of gamma rays and high-energy neutrinos, those nearly massless and chargeless ghost particles that abound across the universe. Sluggish and high-energy do not often go together, but the newly released image offers some fresh clues to help solve the mystery.

“This is the first time we’ve ever got such a clear picture from inside the jet,” says astrophysicist Yuri Kovalev at the Max Planck Institute for Radio Astronomy in Bonn in Germany. “We see emissions all around the central bright region where the supermassive black hole is.” Kovalev is the author of a study in the journal *Astronomy and Astrophysics* that reports that PKS 1424+240 is aligned in such a way that astronomers on Earth can look down the entire length of the jet.

Compiled from data gathered during more than 15 years of precise radio-telescope observations, the image reveals that this particular blazar is pointed almost directly at the Earth, allowing an unprecedented look at what is happening inside. The ringed layers visible in the image represent a donut-shaped magnetic field at the base of the jet, which could be responsible for focusing the jet and accelerating particles like neutrinos. Because the jet is so closely aligned with the

Earth, the high-energy neutrino emission may also be amplified by the effects of special relativity, boosting its brightness. At the same time, the jet may only appear to be moving slowly due to so-called projection effects. This particular optical illusion is why when you look at an oncoming train that is approaching head on, it seems to travel slowly, until it is upon you.



Kovalev and his colleagues have studied this particular blazar since 2009 with a synchronized assembly of 10 radio-telescopes that stretches from Hawaii to the Caribbean. The synchronization of these telescopes means the entire array effectively works like a single radio dish more than 5,000 miles across.

Scientists aren’t sure why the supermassive black holes at the centers of some galaxies form blazars, while most others do not. Kovalev says the new study will help researchers better understand the blazar jets and the powerful, twisted magnetic fields at the center of black holes that are thought to create them.

Blazars are relatively common—astronomers have now detected more than 3,000 of them. But only about a tenth of those emit high-energy neutrinos, which Kovalev thinks are created when relatively heavy



“This is the first time we’ve ever got such a clear picture from inside the jet.”

protons are accelerated to nearly the speed of light near the surface of the supermassive black hole. Protons are relatively massive particles—about 1,800 times heavier than an electron, and billions of times heavier than a neutrino—and the fact that neutrinos are created at all is a clue to the process that creates them. “High-energy neutrinos are a smoking gun for efficient proton accelerators,” Kovalev says, and so better understanding how supermassive black holes can accelerate such massive particles is an “exciting and challenging problem.”

Boston University’s Alan Marscher, a professor emeritus of astronomy who studies blazars but who was not

involved in the study, notes that Kovalev’s suggestion that the neutrinos form near the surface of the central black hole is not the only plausible explanation for them. Instead, the neutrinos may have been created by magnetic shockwaves that occur inside a blazar jet as it expands, he says.

“PKS 1424+240 is a one-of-a-kind blazar,” says astrophysicist Raffaele D’Abrusco of the Smithsonian Astrophysical Observatory, who was also not involved in the study. “This very peculiar blazar happens to have its jet almost perfectly aligned to our line of sight. This specific orientation gives us a chance to directly investigate regions of the jet that are usually not accessible.”

City University of Paris astrophysicist Matteo Ceruti, an expert in blazars, adds that simply capturing the “Eye of Sauron” image is itself extraordinary, because the extreme distance between PKS 1424+240 and Earth means a precise alignment is needed to observe it with radio telescopes: “Getting observational proof of such a tiny viewing angle is an outstanding result.”

—Tom Metcalfe

PSYCHOLOGY

Should We Bring the Dead Back to Life?

WHEN THE *BLACK MIRROR* episode “Be Right Back” aired in 2013, it was clearly a work of science fiction: Tormented by grief after her husband’s death, a woman named Martha orders a robotic replica that serves as his real-life replacement, mimicking his speech patterns and mannerisms.

But as with so much of science fiction, reality often catches up. Over the past decade “griefbots” and deepfake avatars have become commonplace, allowing the bereaved to chat with simulations of their dead loved ones. Now, researchers are exploring something even closer to the *Black Mirror* concept: Virtual reality technology that revives not only the deceased’s image, voice, or way of conversing, but also a virtual simulation of their physical selves.

Unlike most existing grief bots, virtual reality creates the illusion of presence. So even when someone consciously understands that the virtual environment around them is artificial, they often react to it as if it’s real. “If we’re playing a game in VR, and I suddenly throw you a ball, you’re going to try to avoid the ball even if you know it’s not real,” explains Silvia Pizzoli, a researcher who studies grief and VR at the Pegaso University in Italy.

This is its strength and its weakness. Virtual reality has been successfully used to treat mental health conditions like PTSD and anxiety by exposing patients to triggers or feared situations in a safe, simulated environment. Now some researchers believe the technology could also help treat prolonged grief disorder, a diagnosis that has been applied to individuals whose



A bereaved person must remain aware that the person in front of them is a simulation.

grief severely interferes with their daily functioning for at least a year. One type of therapy for this kind of grief aims to help the person develop a healthier bond with the absent loved one inside their imaginations. Clinicians often try an “empty-chair technique,” where patients have a conversation with the deceased while imagining them sitting in an empty chair.

But the empty-chair technique can be difficult to practice because people with prolonged grief disorder often experience intense avoidance of the deceased’s memory, says Francesco Fanti Rovetta, co-author of a recent paper on VR grief technology. Drawing from a large body of grief research, Rovetta’s paper proposes that virtual reality could improve existing grief therapies by getting around this resistance, requiring less of the patient’s imagination. But Rovetta and

colleagues also caution that the technology must be used carefully and only in supervised clinical contexts. Someone in the throes of profound grief risks getting attached to a realistic avatar of a loved one who is gone, which could result in the delusion that the person is still alive.

Rovetta compares this to another kind of imaginal relationship: children’s bonds with imaginary friends. “As long as the child knows the imaginary companion is imaginary, this is pretty much adaptive,” he says. “When the child starts believing that the imaginary companion is actually real, then it can turn into a maladaptive behavior.”

Similarly, a bereaved person must remain aware that the person in front of them is a simulation—something the illusion of presence can make difficult to achieve. In combination, these two effects can cause the bereaved person to develop an “ambiguous attitude” toward the death. The person is aware that the death occurred at a cognitive level but still has an overpowering impulse to deny it.

“One of the major risks I see is that the potential use targets individuals who are already suffering from severe psychological and existential pain,” says Pizzoli. Could VR therapy worsen the pain of this already vulnerable population? It’s something she plans to study in the future. “If we give these people the possibility to meet again [with] the beloved one,” she explains, “maybe we are disturbing the natural, painful process of grief.”



This is the question at the center of it all: How much should outsiders really interfere with the grieving process? Everyone grieves a little bit differently. Some experts believe prolonged grief isn't a disorder at all, but rather the medicalization of a normal and inevitable form of suffering.

The *Black Mirror* episode "Be Right Back" warned of such dangers: At the end of the episode, Martha, disturbed by the inconsistencies between the robot replacement and the husband she remembers, orders his replica to jump off a cliff, finally realizing that keeping him around will only continue to highlight the gap left by her husband without ever managing to fill it.

—Zoe Cunniffe

ZOOLOGY

The Magic of Herding

W

HEN DOYLE IVIE, a 77-year-old farmer and sheepdog trainer in northern Georgia, received an email from Saad Bhamla and Tuhin Chakraborty, two biophysicists from the Georgia Institute of Technology, he was intrigued. The researchers wanted to know if he would let them record the to-and-fro-ing of his sheepdogs.

The farmer couldn't fathom what the scientists might learn about the abstractions of physics by studying his muddy canines, but he agreed. Not long afterward Bhamla and Chakraborty, who study collective behavior, pulled up to Ivie's farm to watch the dogs in action. That day, the farm was hosting a sheepdog trial, a centuries-old competition in which sheepdogs show off their herding skills by steering small flocks of sheep across a field, as well as splitting the group, known as "shedding," among other tasks.

Physicists have studied sheepdog herding for decades, but they have mostly modeled how the dogs gather up large herds, Bhamla says. In these large herds, sheep display what's known as selfish flocking behavior, gravitating toward the center and putting

others between themselves and danger. But in smaller groups, as in sheepdog trials, their decisions become more erratic, as they waver between following the flock or heading off on their own.

How the sheepdogs manage to get the sheep to go where they want under these chaotic conditions suggests a solution to a tough problem in physics—controlling noisy, unpredictable collectives, which is relevant not just to sheep, but also to drone and robotic swarms and pedestrian movements, among other things. Such emergent collectives are driven by both group-level patterns and by interactions between individual members of the group.

"Dogs do amazing things, so naturally we were interested," says Bhamla.

After their visit to the farm, Bhamla and Chakraborty gathered a series of recordings of sheepdog trials from YouTube videos. As they looked for patterns in the recordings and talked with sheepdog handlers, they noticed that both herding and shedding boiled down to a two-step process. In the first step, the dog nudges the sheep gently from a distance without inducing panic, waiting for them to face in the desired direction. In the second step, the dog approaches, increasing the threat to get the sheep to move; instinctively, they flee from the perceived predator in the direction they are facing.

The next challenge for the physicists was translating what they had learned into a mathematical model. Their model included five sheep who changed orientation either in response to a social influence (copying their neighbor), or in response to outside force, such as a dog or a handler. Which influence they chose to respond to was determined at random, though individual sheep were programmed to be more or less responsive to dogs and handlers. The dogs in the model also followed the same two-step process as in real life, first nudging and then moving.

The scientists found that although random behavior is typically considered an obstacle to controlling a small collective, the indecisiveness of the sheep was actually a benefit to the dogs in



Instead of suppressing randomness, they found, the sheepdogs seemed to embrace it.

the “splitting” task. The dogs could simply wait until the sheep were facing in the direction they wanted before closing in, limiting the effort required. Instead of suppressing randomness, they found, the sheepdogs seemed to embrace it.

Based on these findings, the scientists built an algorithm that could be used to predict behavior in other small indecisive behavior-switching collectives. The results, which have not yet been peer-reviewed, were published in June on the preprint server *arXiv*.

Ted Pavlic, a computational biologist and professor at Arizona State University said the findings could apply to any situation where someone needs to guide a group of individuals with whom they can’t directly communicate. “When I’m developing a strategy for a group of individuals that I want to steer, I would assume consistent behavior from all of them,” says Pavlic. “This shows that maybe that’s not the best strategy.”

But Pavlic notes limitations in the model, particularly in how it represents real sheep. For example, the model sheep don’t avoid collisions and can pass through one another. They also don’t remember where they’ve been. “It would be interesting to see what they find if they add these things to the model,” he says.

Raissa D’Souza, a professor of computer science and engineering at the University of California, Davis, praised the scientists’ clever use of real world data and agreed that the findings could be useful in the context of robot swarms, particularly for search and rescue. But she pointed out that the results only apply to a very specific type of physics problem—small noisy systems that feature random switching between two states—and don’t generalize over all examples of small, noisy collectives.

Bhamla and Chakraborty agree that there’s much to learn. In the future, they hope to explore further how individual sheep behavior influences the outcomes. “Animals are so complicated. We’re still just scratching the surface,” Bhamla says. “What I find amazing is that we’ve taken such a seemingly simple competition and made a whole story about it,” Bhamla says. “How beautiful is that?”

—Natalia Mesa



ENVIRONMENT

Orchids Thrive Among the Dead

SCATTERED BETWEEN the gray tombstones of an old cemetery in Aldborough, England, you will find early purple orchids swaying in the shin-high grass. Although farms and cities have consumed much of this species' forest and grassland habitat, the human tradition of laying the dead to rest in terrestrial burial grounds has given this population a place to grow relatively free of human disturbance. A similar pairing can be found across the continent on the Greek island of Crete, where pink butterfly orchids bloom beside the marble crosses that mark graves. The orchid species seems to have found protection among the tombstones.

It's a pattern that repeats across the continent. At least 65 different species of the delicately flowered plants have been identified in the burial grounds of

Europe, according to a study published in *Global Ecology and Conservation* this year. A team of Hungarian scientists meticulously documented orchid diversity across 2,079 cemeteries in 13 European countries spanning from Slovakia to Spain.

Many species of orchids are specially adapted to grow in nutrient-poor meadows where few other plants can survive. But these habitats are disappearing due to fertilizer runoff from farms and the decline of traditional sheep grazing practices that maintain open grasslands. Orchids have been on a decades-long decline throughout Europe.

Most orchids rely on complex relationships with pollinating insects, soil fungi, and even host trees to grow and reproduce, making them exceptionally vulnerable to environmental changes. As a result, they



serve as a kind of bellwether: In places where they do flourish, it is often because the larger local ecosystem is healthy and thriving.

Study author Attila Molnár, a Hungarian botanist, became interested in the morbid relationship between orchids and the dead after he visited several Turkish cemeteries in 2013 that are known among plant enthusiasts as great places to see wild orchids. When he returned home, he pitched a research project documenting the orchids of Turkish cemeteries to his incoming Ph.D. student, Viktor Löki, who said “yes” immediately. “It was tops five minutes,” recalls Löki, now a biologist at the HUN-REN Centre for Ecological Research in Budapest and a co-author of the study.

The team’s research quickly expanded beyond Turkey into the rest of Europe. By 2018, Löki and his colleagues had visited more than 2,600 cemeteries in Europe and Turkey. Their findings contribute to a growing body of research that suggests that cemeteries all over the world are biodiversity hotspots. In fact, cemeteries are some of the most biodiverse habitats in and near cities, says Jenő Nagy, study lead author and biologist at the University of Debrecen, Hungary.

The study is the first-ever assessment of the conservation value of cemeteries on a continental scale. Fifteen percent of the graveyards surveyed contained orchids, and the researchers found 44,680 individual plants. “The fact that so many orchid species occur in European cemeteries was a surprise for me,” says Ingo Kowarik, a plant ecologist at Technische Universität Berlin in Germany.

During the five years Löki spent scouring graveyards for the showy, fragrant flowers, he saw a diversity of attitudes toward allowing scientists into cemeteries. In the mountainous north of Azerbaijan, “they were very supportive [of our research] and they said: ‘you do whatever you want,’” Löki recalls. But just a four-hour drive away in southern Azerbaijan, “people over there were very suspicious,” he says. They would approach us immediately, and when we answered their questions they would tell us to leave, he says.

The traditions of different cultures influence whether their cemeteries play host to orchids and other plants. Many religions prohibit building, farming, and resource extraction on burial grounds. But gravesite architecture matters, too. On the Mediterranean coast

Cemeteries are some of the most biodiverse habitats in and near cities.

of Spain and France, orchids grew in just two of the 150 cemeteries surveyed. Rocky soils and local customs dictate that many bodies rest above ground in structures, such as mausoleums, Löki says. These masses of concrete and marble leave very little open soil where plants can grow, he says.

Some of the groundskeeping practices at cemeteries may also be more orchid-friendly than others, the researchers believe, although they did not have enough data to statistically test this idea. In some places, plants and animals lived largely undisturbed among the tombstones. Other cemeteries are frequently mowed and treated with pesticides to create a lush, green lawn at the expense of biodiversity, Nagy says.

Löki noticed that this kind of manicuring was much more common in Europe than in Turkey, where “they are rather interested in leaving nature alone for religious reasons,” he says. He was fascinated by this fortuitous overlap between spirituality and conservation. The orchids, in any case, are sublime.

—Mark DeGraff



ASTRONOMY

The Heart of a Haunting Galaxy

THIS EERIE SPACE SCENE lives up to its name—the Phantom Galaxy. Officially known as M74, it has a diameter of around 95,000 light-years, nearly the size of our Milky Way. In this image, the spiraling arms made up of threads of dust and gas draw the eye toward the glowing central star cluster—a view typically obscured by gas. These stars are estimated to be about 8 billion years old, just past middle-aged as far as stars go in our universe. Among other twisty galaxies, M74 has some of the most crisply defined arms.

This ghostly galaxy was first observed in 1780 by the French astronomer Pierre Méchain, who worked with renowned comet hunter Charles Messier. M74 lives some 32 million light-years from our planet, and we can view it nearly directly—so astronomers often look into its haunting depths to learn more about spiral galaxies. This image was captured by the James Webb Space Telescope.

As part of a global research collaboration called Physics at High Angular resolution in Nearby GalaxieS (PHANGS), Webb has been wielded to probe neighboring star-forming galaxies like M74 with its powerful infrared imaging to unlock the secrets of stellar births. In recent years, PHANGS scientists have taken a closer look at the Phantom Galaxy's mysterious features—for one, it contains more than 1,600 gaping holes measuring up to 3,600 light-years in diameter. These rips potentially formed from bursts of energy shot out by dying stars or by the howling winds released by infant stars. These holes may perforate other galaxies, too, some of the PHANGS researchers suggest.

This team has also posited that infant stars may remain swaddled in their cosmic baby blankets composed of dust and gas for some 5 million years. This conceals them from visible-light telescopes such as the Hubble Space Telescope, which produced earlier, less crisp, images of M74. But thanks to the sharp infrared vision from James Webb, we can continue to glean insights on the earliest stages of stellar lifespans.

—Molly Glick

Image by ESA / Webb, NASA & CSA, J. Lee and the PHANGS-JWST team.



More Than a Feeling

How awe and wonder transform science and you

BY SEAN B. CARROLL

A

ND THE OSCAR GOES TO ...”

A lifelong biologist, never in my wildest dreams did I imagine myself strapped into a tuxedo at the Academy Awards, heart racing, about to hear whether a film I worked on would win a coveted gold statuette.

Especially for this film. It was a tale of two young brothers in Delhi battling poverty and prejudice who dedicated their lives to treating injured birds. But the opening scene showcased neither the brothers nor the birds, but instead one very long night shot of an abandoned lot ... full of rats. As the film’s executive producer, all I could picture in my mind were thousands of potential viewers turning the channel to watch something else, anything else. And I spent a fair amount of time during the editing phase ranting to my colleagues how the first five minutes of the movie were killing any chances of it ever being seen by anybody, anywhere.

Was I ever wrong, stupendously wrong.

One critic began their review by declaring, “The opening shot of Shaunak Sen’s documentary *All That Breathes* is probably the most beautiful and unnerving thing I saw at this year’s virtual Sundance ... What follows is one of the more dreamily provocative documentaries I’ve ever seen.”¹

ILLUSTRATION BY TARA ANAND



ALL THAT BREATHES

A makeshift clinic for injured birds in a family garage in Delhi is the setting for the documentary, *All That Breathes*. By pulling us into a strange world, the film is a powerful manifestation of awe.

The film ended up winning the Grand Jury Prize at Sundance, then the Documentary Prize at the Cannes Film Festival, which launched a magical journey for the brothers, Nadeem Shehzad and Muhammad Saud, and the film team, and a new education for me, as I tried to understand why critics and audiences so willingly and widely opened their hearts to this film.

Eventually, thanks to revelations from psychological research, I got it. I now recognize that director Shaunak Sen and cinematographers Benjamin Bernhard, Riju Das, and Saumyananda Sahi had managed to evoke the powerful experiences of awe and wonder—and in some of the most unexpected and unlikely places. They brought viewers inside a makeshift clinic in a cramped family garage, to be awed by the brothers' tireless devotion and tender compassion. Outside, the city air is chokingly opaque. But with scenes of black kites, owls, horses, cows, monkeys, turtles, and—yes—rats sharing that harsh environment, the filmmakers elicit wonder at the marvelous richness, even there, of “all that breathes.” Being pulled out of ourselves into another world, viewers experience what psychologists call self-transcendence, a powerful manifestation of awe.

But awe and wonder are much more than just nice feelings or coveted reactions in audiences. A current surge of scientific and popular interest in awe, including two recent books,^{2,3} is being spurred by the discovery of a surprising array of positive psychological and social benefits to awe experiences, benefits that strongly suggest we all need more awe and wonder in our lives.

Awe and wonder are the prime emotions that spark and sustain scientific exploration, discovery, and creativity.

Research reveals that awe and wonder are the prime emotions that spark and sustain scientific exploration, discovery, and creativity, that motivate science learning, and that inspire the public's interest in science and nature.

At a time when public support for science in the United States is in jeopardy, scientists, educators, and science communicators need to better understand how to reach people at an emotional, not merely an intellectual level. Here, I explore these powerful emotions at the heart of the scientific enterprise—how they are triggered, shape our outlook and behaviors, and how and where everyone can find more awe and wonder.

THE SCIENCE OF AWE

Recall an intense experience when something stopped you in your tracks or took your breath away, when you may have felt goosebumps, your heart race, or perhaps audibly gasped “whoa.” Bask again in that moment before reading on.

Now consider, just what is this feeling? Why did it arise? And what impacts did it have on your mood, outlook, or behavior?

These are the questions that awe researchers are exploring.

Like fear, joy, or anger, awe is recognized as a distinct emotion commonly defined as a feeling of being in the presence of something vast (either perceptual or conceptual) that transcends one's current understanding of the world, something greater than what we are used to experiencing that causes us to shift our mental frameworks.

A rare and typically fleeting feeling, awe may be either positive “in the upper reaches of pleasure,” as two awe researchers put it, or negative when evoked by a threat (a tornado or earthquake).⁴ Individuals experiencing awe describe a sense of a “smaller self,” of being in the presence of something greater than oneself, that resituates them as individuals within larger contexts (a group, humanity, the planet, the universe).⁵ Neil Armstrong, while on his way to the moon to experience perhaps the most profound individual awe moment in human history recalled:

It suddenly struck me that that tiny pea, pretty and blue, was the Earth. I put up my thumb and shut one eye, and my thumb blotted out the planet Earth. I didn't feel like a giant. I felt very, very small.⁶

We just might tell a story that moves people the whole world over.

While the vastness of space or the physical beauty of nature may be the kinds of experiences that first come to mind, sources of awe are much broader. Consider the estimated 650 million people around the globe who gathered on that summer day in 1969 in front of television sets to see the live, grainy, black-and-white images of Armstrong set foot on the moon and hear him utter the immortal phrase, “That’s one small step for a man, one giant leap for mankind.” What were they feeling (or I should say “we” as I was also watching)?

Most certainly awe, but for different reasons than Armstrong himself. Dacher Keltner, pioneering awe researcher at the University of California, Berkeley, and his colleagues asked 2,600 individuals from 26 countries (representing 20 languages) what evoked their most intense feelings of awe.

The researchers identified eight common categories of physical, social, or cognitive stimuli that elicit awe. One might anticipate that beauty in nature would top the list, but the researchers found that what they termed “moral beauty”—the courage, kindness, compassion, resilience, or extraordinary abilities of other people—the virtues we associate with heroes like Armstrong or altruists such as the bird-rescuing brothers, was the most cited source of awe.² A second major category of awe was collective gatherings and experiences such as dancing at weddings, singing together in church, or rooting at sporting events. And the six

other major sources of awe identified by Keltner and colleagues include nature, music, art and visual design, spiritual and religious encounters, life or death encounters, and big ideas or epiphanies.

Scientific interest in awe is being driven by the discovery of a remarkable spectrum of psychological effects and behaviors that are evoked by these experiences and the sense of a smaller self. These include many positive co-occurring states of mind including greater humility,⁸ gratitude, compassion, and optimism,⁹ an increased sense of belonging, well-being and overall appreciation for life,¹⁰ and sometimes even profound, life-altering changes in perspective and direction.^{3,4} From these feelings, people then also seem more inclined to prosocial behaviors including greater generosity,¹⁰ helping others,¹¹ collective engagement,⁵ and pro-environmental attitudes and intentions.¹² Awe’s cognitive, emotional, and behavioral effects prompt some psychologists to view these experiences as antidotes to the struggles of daily life and even societal conflicts.^{13, 14}

Wonder has a close relationship to awe, but it is distinguished from it in two important ways. First, wonder is a cognitive state that arises out of an awe experience. Wonder is manifested as curiosity, an openness to novelty, and a desire to explore the unknown that awe has exposed. That is, “I am in awe and therefore I wonder ...” (Or another way to look at it: Awe blows the mind; wonder is the drive to try to figure out how to put it

back together.) Second, wonder is also viewed as a “quieter, less spectacular emotion” than awe,¹⁵ that does not require the dimension of vastness and can arise independently from awe. We may feel wonder encountering phenomena or objects such as a geyser, a fossil, or a handsome owl in the middle of Delhi—even without experiencing a more dramatic state of awe first.

What wonder and awe both do is help us to recognize gaps in our knowledge.^{5, 15} “Wonder lies at the edge of knowledge,” philosopher Helen De Cruz writes in *Wonderstruck*, “it opens vistas to the unknown by directing our attention to it.” In encountering the unknown and under the influence of these emotions, we become aware of mystery. According to Einstein, this is where science begins:

The most beautiful thing we can experience is the mysterious. It is the source of all true art and science. He to whom this emotion is a stranger, who can no longer pause to wonder and stand rapt in awe, is as good as dead: His eyes are closed.¹⁶

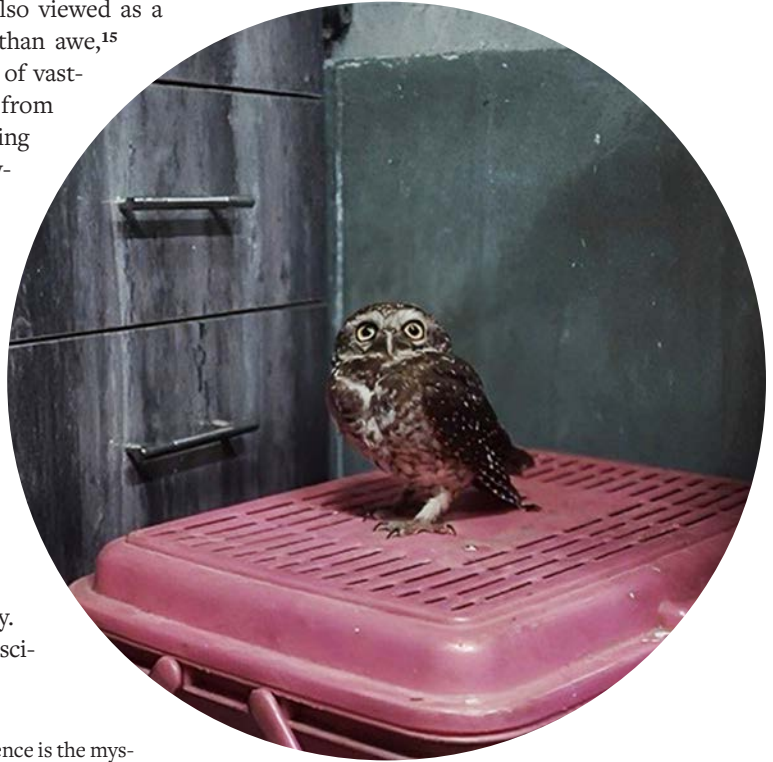
THE AWE OF SCIENCE

Many scientists before and since Einstein have acknowledged the roles awe and wonder have played in spurring their scientific lives.^{17, 18} The experience that University of California, Berkeley, ecologist Mary Power recalls is both unique and typical:

When I was a child, I was severely myopic from who knows what age ... But something happened before I got glasses, and that was that I was let loose with a mask and snorkel. For the first time, I saw things clearly because of the refraction of the water.

You can imagine how beautiful it would be when you see detail that you’d never known you could see. What were pondweeds above the water were forests of stems under the water. And in this little forest, there would be sun fish. Then occasionally, a big, larger predator like a pickerel or a perch or a bass goes by.

It was a flashbulb moment, as they say, where I just had to be underwater looking at life that way, for the rest of my life.¹⁹



BIRD CARE

Another still photo from *All That Breathes* underscores the tenderness and compassion shown by brothers Nadeem Shehzad and Muhammad Saud in treating birds in the polluted city.

Awe turns to wonder on the Serengeti.



This vivid and emotionally arousing flashbulb moment would inspire Power's pioneering studies of freshwater stream communities, within which she was the first to demonstrate the operation of what ecologists call a trophic cascade—a domino-like series of interactions through a food chain.²⁰ Five decades later, she continues to look at life underwater.

A similar moment to Power's inspired my book *The Serengeti Rules*, later adapted into a film. A decade ago, I visited Serengeti National Park in Tanzania for the first time. I vividly recall being awestruck while gazing at the astounding numbers and variety of wildlife across the landscape. Nothing I had read or seen on television diminished the power of the vista. But it also dawned on me, a molecular biologist, that I had no idea what I was looking at, of how the Serengeti worked, nor whether anyone knew much about it. My awe turned to wonder, and that's how I learned of pioneering zoologist Tony Sinclair's insights into Serengeti ecology, work that was inspired by his own Serengeti awe experience five decades earlier:

Nothing had prepared me for the experience of wildlife in vast numbers, the extraordinary migrations, the sheer diversity of animals and vegetation, and the spectacular landscapes. I decided then that I would spend the rest of my life studying this ecosystem and why it was like the way it was. It was without a doubt in my mind the most extraordinary place on Earth.²¹

Having written stories and helped to make films about scores of scientists, I could fill countless pages with similar anecdotes. And research psychologists are now investigating why and how such experiences influence the practice of science itself.

In detailed interviews with 30 people with Ph.D.s across a wide swath of disciplines and career stages, Megan Cuzzolino of Harvard University probed the role of awe in their scientific journeys.¹⁸ She found abundant support for awe in sparking the desire to become scientists, arousing curiosity about the subjects they chose to explore, and sustaining their motivation to pursue science. Their experiences had many sources spanning several of the eight categories above. For example, awe was inspired by direct firsthand encounters with natural phenomena as well as through secondhand learning about other discoveries that elicited awe for the discoverers (moral beauty) and/or the new big ideas they offered (epiphany).

Many scientists also cited being part of the broader scientific community as a source of awe, viewing their efforts as a small way of helping the larger collective enterprise of expanding human knowledge. "It's my contribution on the path that as human beings—with humility, with difficulties, with resilience—we keep following for a bigger goal. So the awe is not in what I have done, the awe is in the process," said one interviewed neuroscientist. Similarly, an astrophysicist described themselves as part of "a social community of human beings that are in this together to figure out how the universe works. You're really rooting for people to figure things out. Even if they're in competition with you!"¹⁸

Numerous scientists also recalled moments of scientific discovery as sources of awe, and described how by making observations with their own eyes they could relish a brief period when they are the only one to see or to know something. Large or small, these epiphanies are treasured as the rewards for long periods of effort and uncertainty, and they stoke the desire for more such moments.

Awe and wonder have been found to promote attitudes that are conducive to scientific discovery itself, such as openness to new phenomena, ideas, and explanations, and to shifts in perspective¹⁸ while reducing reliance on established notions.¹⁵ A disposition to awe is associated with increased creativity and creative personality traits.^{22, 23} The most consistent and strongest personality trait associated with creativity, in fact, is openness to experience²⁴—which is reflected by intellectual curiosity, a willingness to try new things, and openness to emotion. We can appreciate how awe and wonder spark and sustain the entire journey of scientific discovery and invention, from “what if?” to “a-ha!” from the initial perception of a mystery, through its exploration, to exhilarating moments of seeing what no one has seen or understood before.

Researchers who found that a disposition toward awe is associated with a better understanding of the nature of science and with scientific thinking even boldly suggested that awe is “a scientific emotion.”²⁵ Surely this term will strike some as an oxymoron, the scientist-archetype persisting as a person striving toward pure facts and reason, not emotion. But psychological research is telling us that under that veneer of dispassionate rationality lies a strong yearning for—and connection with—awe and wonder, shared with the rest of humanity.

For everyone, scientists and nonscientists alike, Keltner offers one all-caps prescription for those seeking a richer life, a greater sense of purpose and meaning, and stronger bonds to the communities and natural systems that support us: FIND AWE. He means more than a once-in-a-lifetime experience such as seeing the Grand Canyon. Rather, he points to more accessible, potential everyday sources of awe such as music, art, or nature.

But what about science itself as a source of awe and wonder? The entire journey of scientific exploration

as well as scientists’ own stories—as people who venture into the unknown, take risks, and persevere through frequent failure to experience the exquisite thrill of discovery—are themselves potential sources of life-enriching awe and wonder.

There is, however, an issue of accessibility for non-scientists. As science communication scholar Michael Dahlstrom points out, “In the end, only scientists can know science through science. Everyone else must learn about science through other means.”²⁶ So, how can scientists convey and non-scientists experience, as Richard Dawkins described, “this feeling of spine-shivering, breath catching awe ... this flooding of the chest with epiphanic wonder, that modern science can provide?”²⁷

THE POWER OF STORIES

“Scientists say that the world is held together with atoms, and of course, it is. But it is also held together with stories.”

—Colum McCann, *American Mother*

On June 6, 1990, astronomer Carl Sagan stepped to the podium at NASA Headquarters in Washington, D.C. to give a press update on the findings of the Voyager Mission (launched in 1977) to the outer reaches of our solar system. He introduced a mosaic “portrait of the planets” taken by Voyager 1 as the spacecraft cameras looked back across the solar system from more than 4 billion miles away. He then turned to one image with several colored streaks across it, and pointed to a tiny bright speck:

The Earth in a sunbeam ... It looks like more than a dot, but it is in fact less than a pixel ... You can see that it is slightly blue, and this is where we live, on a blue dot ...

After a few remarks about other planets, Sagan returned to the Earth’s image:

On that blue dot, that’s where everyone you know and everyone you ever heard of, and every human being who ever lived, lived out their lives. It is a very small stage in a great cosmic arena ... I think this perspective underscores our responsibility to preserve and cherish that blue dot, the only home we have.

PALE BLUE DOT This wondrous NASA photo of Earth taken from the Voyager spacecraft, Carl Sagan said, “underscores our responsibility to preserve and cherish that blue dot, the only home we have.”



Judged solely on aesthetic merit, one might dare to say that at first glance it was perhaps not the most impressive snapshot. In fact, Voyager imaging scientists Candy Hansen and Carolyn Porco initially either did not see the Earth on the image or mistook it for a speck of dust.²⁸ Sagan and other NASA scientists knew that the picture had no scientific purpose. Yet, the Earth as a Pale Blue Dot stands as one of the most enduring icons of the modern scientific era.

What insights might we glean from it to learn about the source of its power? Let's consider what elicitors of awe might be at work. Here are four candidates.

- Nature: The image of our tiny planet in the dark immensity of space evoked vastness and the small self on a new scale. Astronomer and author Jim Bell wrote, "Once again the citizens of Planet Earth, then numbering about 5 billion, bore witness to the next great paradigm-shifting change in perspective. This time it was not just off-world, not just from beyond our backyard, but a vista from out there."²⁹
- Art and visual design: The less-than-a-pixel Earth in a sunbeam was a surprising, never-before-seen or imagined image, a new space "artwork" with an emotive moniker.
- The virtues and abilities of others: Sagan related how this image was only made possible by the combined efforts and ingenuity of teams of scientists and engineers who had devoted many years of their lives to the mission—a heroic human achievement.
- Big idea or epiphany: Sagan's poetic eloquence elevated the power of the image and the moment by focusing on the meaning of that tiny blue dot to every person, transforming an image of admittedly no scientific significance into a global epiphany.

While any one of these elicitors may have been sufficient to evoke awe, it seems very likely that their combination multiplied the overall power. That power remains undiminished more than three decades later, and now psychology researchers have studied subjects' responses to Sagan's Pale Blue Dot narrative in conjunction with other images of space.³⁰ In addition to awe, subjects report feelings of compassion, gratitude, love, optimism, greater connectedness, and humility.

This positive emotional wallop suggests that scientists (as well as science teachers and science communicators) have potentially much more emotive power within our reach than we may realize. How can we grasp and deploy it most effectively?

Albert Camus, the inspirational voice of the French Resistance and 1957 Nobel Laureate in Literature knew the secret: "The first thing for a writer to learn is the art of transposing what he feels into what he wants to make others feel."³¹

One of the most important features of the human mind is our ability to feel what others feel—and we do this most effectively through story. The most powerful reason anyone writes or reads stories, tells or listens to stories, or makes or watches films is to evoke or experience emotions.

Planetary scientist Porco credits Sagan, who was also a Pulitzer Prize-winning writer, with turning the revelation of Voyager's photograph into

Awe and wonder
spark and sustain
the entire journey of
scientific discovery
and invention.



“an allegory on the human condition”—making it a *story* about us, summoning our thoughts and feelings about everyone we know and the limited time we have on our unique, precious, common home.²⁸

What was instinctual to Camus and Sagan is now backed by decades of research in narrative psychology which seeks to understand how stories and storytelling shape our understanding of the world. The power of stories to evoke a flurry of emotions stems from their abilities to transport and immerse audiences into worlds created by the storyteller.³² Research suggests that transportation, the feeling of being carried away by a story, occurs most effectively when audiences empathize with characters and experience the plot of the story through them. Immersion, a state of deep mental absorption and subjective sense of “being there,” further supports this when the imagery of a story compels the audience’s mental imagery to shift their attention from their immediate surroundings into the story world.

For any experience, for any audience, story is the next best thing to being there. For science, for the vast majority of audiences, story is the *only* way of being there. And science stories work best when the emotion and substance of that experience is conveyed in ways that elicit the audience’s emotions. So, to Keltner’s prescription, I add one all-caps suggestion for where to find more awe: IN STORIES.

Sagan, whose landmark television series *Cosmos* was seen by a global audience of 500 million, worried deeply about the public’s and politicians’ valuation of science and foresaw the making of today’s crisis. In one of his last major public addresses before he died from cancer at age 62, when asked about how to best champion and support science, he urged:

To present science as it is, as something dazzling, as something tremendously exciting, as something eliciting feelings of reverence and awe, as something that our lives depend upon.³³

The stakes for science, for our Pale Blue Dot and all the creatures living on it, and those yet to come, have grown since then. But with some effort, every now and then, we just might tell a story that moves people the whole world over.

Speaking of which, we didn’t win that Oscar. But that was okay. It was an awesome night. ☺

SEAN B. CARROLL is the Balo-Simon Endowed Chair and Distinguished University Professor of Biology at the University of Maryland. He founded and led HHMI Tangled Bank Studios from 2018 to 2023.

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FLASHBULB MOMENT

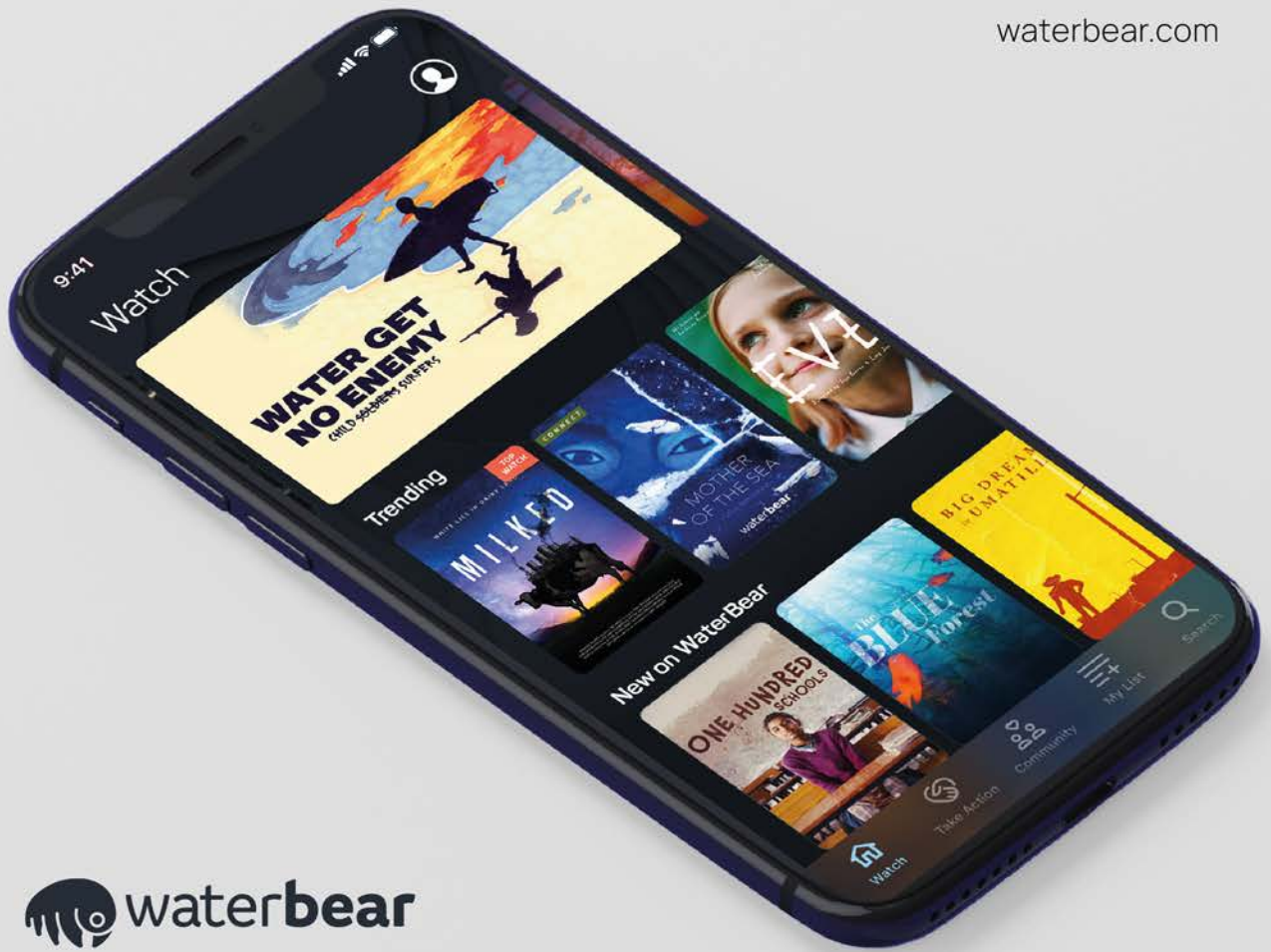
The awe of underwater nature, ecologist Mary Power said, inspired her life in science: “It was a flashbulb moment, where I just had to be underwater looking at life that way, for the rest of my life.”

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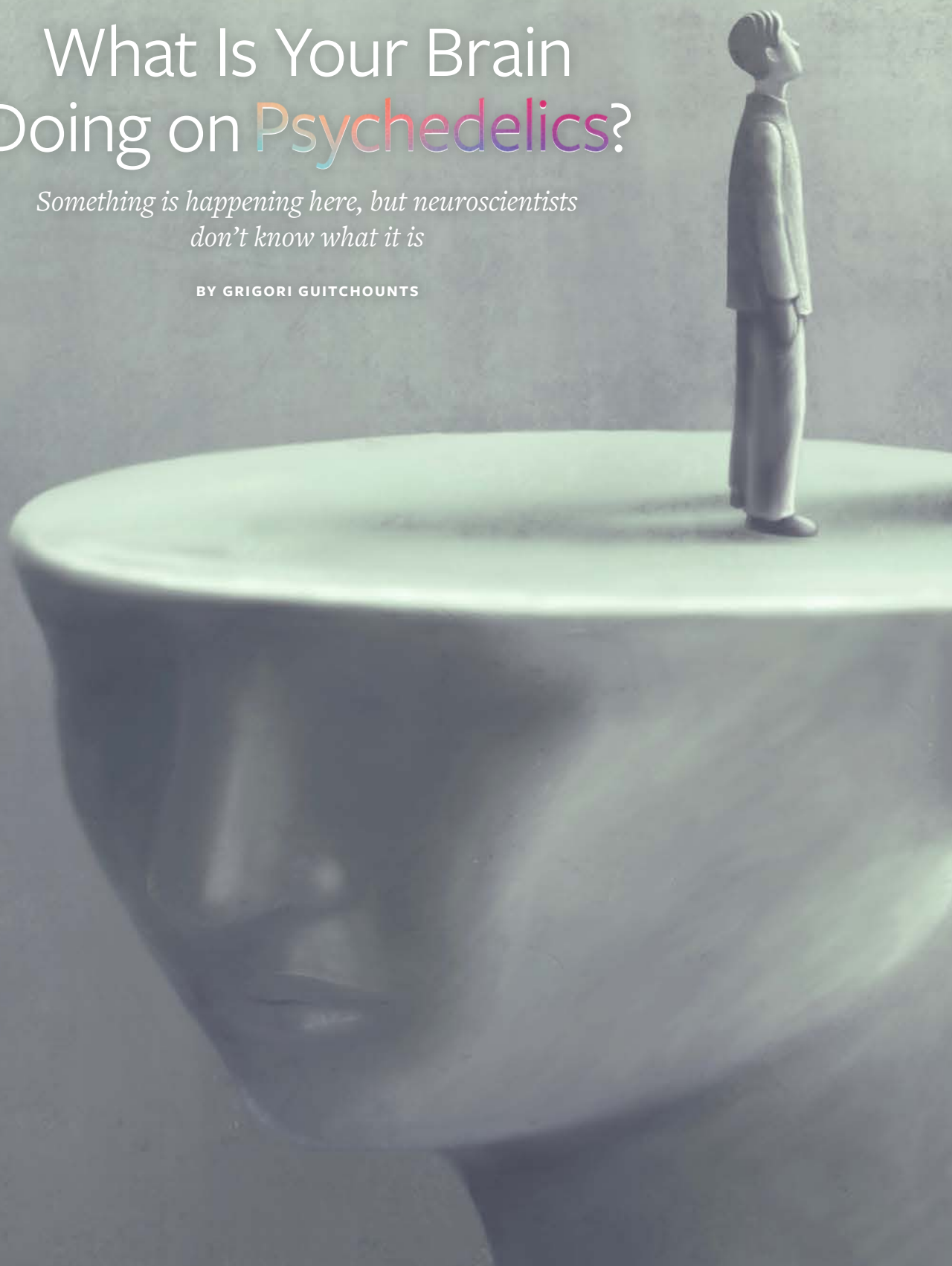
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*Something is happening here, but neuroscientists
don't know what it is*

BY GRIGORI GUITCHOUNTS





IN A MELLOW SPRING NIGHT, I gazed at the setting desert sun in Joshua Tree National Park in California. The sun glowed a warm blood-orange and the sky shimmered pink and purple.

I had just defended my Ph.D. in neuroscience, and my partner and I had flown west to celebrate and exhale. It was early March 2020, and we were hoping to quiet our minds in the desert. I was also hoping to change mine.

I had been curious about psychedelics for years, but it wasn't until I read *How to Change Your Mind* by Michael Pollan about the new science of psychedelics, that I felt ready. The book made a compelling case that psychedelics provided a fascinating introspective experience. Still, I was nervous. I'd heard stories about bad trips and flashbacks. I knew enough neuroscience to know these were serious drugs—compounds that could temporarily dismantle how the brain makes sense of reality and potentially change it irreversibly.

I also knew I was burned out. My Ph.D. had been hard in the way Ph.D.s often are: thrilling, lonely, disorienting. My advisor had left academia halfway through, and I'd spent years without much supervision, never quite sure whether I was on the right track and if I had a future in academia. But I didn't take LSD seeking healing or clarity. I just wanted to see what the fuss was about. After years of hunkering down, I was craving a freeing experience.

We put on Bach's Partitas for keyboard, wrapped ourselves in Navajo blankets, and waited.

The air shimmered. The little bird dolls hanging in the cabin started telling me their secrets.

What followed was strange, intense, and beautiful. The wooden floorboards of our cabin turned into a bustling cityscape. The mirror in the bathroom showed my face aged beyond recognition: The natural lines in my skin became deep wrinkles, my eyes sunken, as if time had decided to give me a sneak peak of what would come. Later, absorbed with coloring pencils, I watched the marks I was making dissolve in real time, as if the paper were being erased by invisible rain.

The air shimmered. The plants breathed. The little bird dolls hanging in a corner of the cabin started telling me their secrets. My body felt porous, as if boundaries had loosened. I didn't fully lose my sense of self, but I did feel a kind of communion—with the rocks, the scrub, the sky. It was deeply, inexplicably moving. Everything was love.

AS A NEUROSCIENTIST, I can't help but wonder what was happening in my brain on acid. Was my default mode network—a network of brain regions most active

when our minds are at rest, drifting through memories, daydreams, and self-reflection—collapsing, as Pollan had described? I wasn't sure. What I did know was that my perception had changed, not just in content, but in form. My brain was generating coherent sights, emotions, meanings, all from its own imagination, based on my prior experiences. It all seemed both impossibly real and completely made up.

Neuroscientists have tried to explain experiences like mine by turning to physics. Robin Carhart-Harris, a professor of neurology, psychiatry, and behavioral sciences at the University of California, San Francisco, and one of the most influential figures in the psychedelic renaissance, believes that psychedelics increase the brain's entropy—a term borrowed from thermodynamics that, loosely speaking, refers to disorder or unpredictability.

According to Carhart-Harris, normal waking consciousness is governed by structured patterns of brain activity: Certain regions talk mostly to each other,

networks like the default mode network enforce order, and the brain efficiently predicts the world around it based on experience.

Psychedelics, he argues, disrupt this order. The brain becomes more chaotic, more fluid. Rigid beliefs loosen. Novel connections emerge. Freud's ideas on the id and the ego—particularly the ego's role in imposing order on unruly unconscious drives—inspired in Carhart-Harris a language to frame the psychedelic state as a temporary loosening of the ego's grip, reflected in fMRI data as a breakdown of brain organization.

The therapeutic effect of psychedelics stems from this breakdown. "The principal component of mental illness is 'stuckness,' this rootedness of thoughts, feelings, behaviors that characterizes so much of psychopathology or mental illness," Carhart-Harris told me. To cure afflictions ranging from depression to PTSD, eating disorders to OCD, the mind and brain must get un-stuck. And this is where psychedelics shine: "Psychedelics promote plasticity," Carhart-Harris said. "Formally, a definition of plasticity is changeability, the ability to change."

And that presents an exciting question, Carhart-Harris said. "How does the entropic brain phenomenon relate to plasticity? I see the entropy of spontaneous brain activity as the thing that we can modulate acutely. It's like an entropy dial: Dial it down and consciousness drops; dial it up, consciousness enriches."

His model has appeal. It offers a story that links molecular action to neuronal networks to psychology. And it matches up beautifully with the kinds of testimonies that began to surface in clinical trials and across media accounts of the psychedelic renaissance: the feeling of becoming unstuck, the flood of insights, the sense of seeing clearly for the first time. Rachel Drayer, a physician assistant in emergency medicine, told me how her psilocybin experience in a clinical trial helped her shed the anger and depression that had burdened her since working on the frontlines of the COVID-19 pandemic.

But what if Carhart-Harris' model is not what's happening in the brain?

As the psychedelic renaissance has matured, a different kind of conversation has begun taking shape. Some neuroscientists have started raising

uncomfortable questions: Were these theories supported by the data? What, exactly, was being measured when researchers claimed an increase in entropy? And how solid was the foundation beneath this shimmering structure of metaphor and model?

The critiques didn't question whether psychedelics had real, even life-changing effects. They questioned whether we understood why. And whether the neuroscience story the researchers had been telling—to patients, clinicians, funders, and the public—was grounded in a robust interpretation of the observed changes in the brain.

ENTROPY, WHEN APPLIED TO the brain, is a slippery concept. In physics and information theory, entropy is a measure of uncertainty or complexity—like the difference between a clear radio signal and one filled with static. A pure tone has very low entropy; a song clearly transmitted has medium entropy; pure static, with no pattern at all, has high entropy. In neuroscience, it often depends on what exactly is being measured—fMRI signals? EEG rhythms? Is it the uncertainty of coordination among brain regions? Or perhaps the randomness of a neuron's firing over time?

To understand how fuzzy this is, picture a jazz band. A highly ordered brain might resemble a tight ensemble playing a familiar tune, with each musician sticking to their role. A more entropic brain might sound like free jazz, with unexpected riffs, shifting rhythms, new combinations emerging on the fly.

That captures the vibe. But what exactly are we measuring? Is it the unpredictability of a single player? Or the variability in how two players coordinate? Or the diversity of patterns across the whole band? In the brain, depending on what signals you record—fMRI, EEG, spikes, synchrony—and what questions you ask of them, you'll get different measures, and possibly different answers.

"Entropy means how predictable is my next state from my previous ones?" said Amy Kuceyeski, a professor at Weill Cornell Medicine. The challenge is determining what aspect of brain signaling is being measured by entropy.

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PSILOCYBIN LIFTED HER BURDEN

W

hen the COVID-19 pandemic erupted in 2020, Rachel Drayer was on the frontlines. She was a physician assistant in emergency medicine at a large hospital in the Seattle area. Patients poured in every day, sick and dying from shortness of breath.

"I wore the same N95 mask for three weeks," Drayer, 48, told me recently. She stored it in a paper bag between shifts. "I worried every day about dying. People just like me, fit and healthy, were dying."

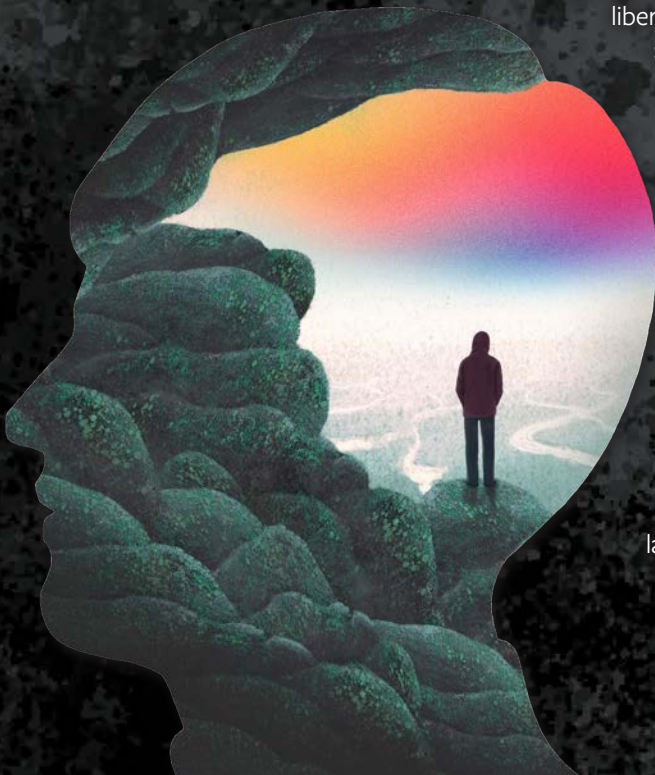
For months on end, Drayer weathered the worst stress she had ever felt. Then things got worse. The atmosphere in the hospital and city changed. "Initially people were pretending to be really kind and supportive, and then people got vile and angry and so selfish and mean," Drayer said. "It was really hard for me to wrap my head around why people would act that way."

Constantly angry, burned out, and depressed, Drayer moved to a rural town in Washington state to work in a community hospital. She thought the change would do her good. It brought her to a new level of dejection. Patients were now complaining that Covid wasn't real, it was a government conspiracy.

"I went from managing really scary trauma situations to being told that I was part of some governmental lie to fleece people out of, well, I don't know what," Drayer said. "I tried to be nice, but I had to say there's no way you're going to convince me that this is fake or contrived or a liberal hoax because I'm pretty sure that I was not shoving tubes down people's throat for fun."

Drayer had become an emotional zombie by 2022. At the time, she said, all she could think was, "I don't want to feel like this anymore. I'd like to have joy back. I'd like to have lightness. I want to be able to laugh and cry. I want to feel anything."

When Drayer learned about a clinical trial in 2022 to take psilocybin to relieve burnout and depression, she signed on the dotted line without hesitation. The clinical trial was designed for people exactly like her: healthcare workers who labored on the Covid frontlines. She also laughed at the prospect, she told me. "Oh,



“I’d like to have joy back. I want to be able to laugh and cry. I want to feel anything.”

somebody wants to pay me to get high? OK, cool.”

Before the “medicine day,” Drayer said, the trial’s researchers explained to her why she made a good candidate. They told her, she recalled, “You don’t have a long neurobiological history of this kind of depression and stress, which tells us that your brain is not necessarily predisposed to feeling this way. This is an acute stressor that’s causing this. If we can rewire your brain and convince it not to feel this way, it’s probably going to work.”

The six-hour trip surprised Drayer. “My journey had nothing to do with the hospital or Covid,” she said. “It had nothing at all to do with anything current.” She encountered what she described as “the three mothers of the universe” who showed her that her job was to give light to others. She watched them remove her soul—“this beautiful egg-shaped white light”—from her chest, explain it to her, and nestle it back “in this nest of blankets.”

“It was healing childhood wounds,” Drayer said. “It was understanding my place in the world. It was understanding my gifts in the world. It changed my life.”

Drayer’s story is representative of the renaissance in psychedelic medicine. Drugs like psilocybin promise something extraordinary: a rapid, almost magical relief from mental afflictions that resist conventional treatments. But scientists now challenge that narrative. The scientists suggest it may not be changes in brain activity sparked by psychedelic drugs that

explains their therapeutic value, but the subjective experience—and aftermath—of being high.

Drayer agreed the drug wasn’t doing all the work of her recovery. Prior to her psilocybin trip, she said, “the work I did with a therapist trying to figure out how to separate my personal life from my work life and learn how to be softer and not so harsh, primed my brain for change more than anything. I was ready to make a change. I was in a perfect place and time for this.”

The lasting power of her psychedelic journey, Drayer said, has been reliving it. Six months after the clinical trial, she began experiencing what felt like panic attacks. “I was like, ‘What does this mean?’ And then I realized the thing I experienced during my journey, that’s what it means. I had a moment of clarity and then my whole body calmed down again. And I could just carry on.”

Today, Drayer said, she is no longer consumed by anger at hospital rules like the maximum amount of time she can spend with patients (20 minutes). “I realized that’s not where I should spend my energy, because that energy is not coming back to me in any positive way.” Now she focuses on patient care, has dropped to half-time at the hospital, and opened a private clinic focused on health and wellness. “The whole vision for the place and what I should be doing came from my journey,” she said.

— Grigori Guitchounts

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Kuceyeski used Carhart-Harris's LSD and psilocybin fMRI data to craft an analysis that treats brain states as a dynamical system. The brain is never static. It constantly shifts between different states, such as those relevant to reasoning or solving problems, or ones that guide muscle control and movement. Scientists can map the shift between states by quantifying the energy used for the transition. They refer to this as "control" or "transition" energy.

Kuceyeski and her team found that brain activity generally clustered into two large-scale networks—one focused on planning and the other on attention. They discovered that relative to placebo, LSD and psilocybin lowered control energy and shifted brain activity from planning to attention, a dynamic that normally quiets our inner executive. Kuceyeski told me the flattening of the brain's control energy correlates with an increase in entropy.

"I think it's measuring the same thing, to be honest," she said. "People who have bigger decreases in transition energy also have larger increases in entropy."

Yet Kuceyeski did not find a correlation between the lessening of transition energy and the subjective experience. While a rise in entropy and drop in transition energy seem to overlap, they don't seem to have the same relationship to the strength of the psychedelic experience.

The overlap has another problem: If two supposedly distinct metrics—entropy and control energy—are capturing the same underlying signal, it's unclear which one, if either, reflects a meaningful mechanism. Without conceptual clarity or empirical separation between metrics such as these, it's hard to know what exactly we're measuring when we look at a tripping brain.

A different kind of conversation about psychedelics has begun taking shape.

The entropy story has other troubles. In some datasets it appears that entropy is increased during a trip, and that it scales with the intensity of the subjective experience. But the proper way to demonstrate that dialing entropy up leads to enriched consciousness would be to increase entropy directly, perhaps through some electrical or other stimulation of neurons, and observe the resulting

changes to conscious experience. Such an experiment is nightmarishly difficult to design and implement and hasn't been performed. Without it, we haven't ruled out that a third factor mediates both entropy and the subjective experience, and that entropy of brain activity doesn't affect conscious experience.

A recent study from a group in Copenhagen evaluated 13 different ways to measure entropy from fMRI data collected from patients under the influence of psilocybin. Only 3 of the 13 showed reliable increases of entropy during the trip. Others, including many of the static or region-specific metrics, didn't change at all. Rather than supporting a brain-wide shift into chaos, the results suggest that any increase in complexity depends entirely on how—and where—you look.

Last year, Joshua Siegel and colleagues at Washington University collected fMRI scans before, during, and after psilocybin or an active control (methylphenidate, aka Ritalin). During the trip itself, brain-wide entropy rose in lockstep with self-reported mystical experience scores. But after the trip, entropy returned to baseline. "Preliminary efforts to identify network changes in the weeks after psilocybin have yielded mixed results," the authors wrote in *Nature*.

Manoj Doss, an assistant professor in the Department of Psychiatry and Behavioral Sciences at the University of

As a neuroscientist, I can't help but wonder what was happening in my brain on acid.

Texas, Austin, explained to me that the apparent increase in brain complexity, or entropy, during a psychedelic trip could be misinterpreted by researchers. Doss has studied the effects of various psychoactive drugs—including psychedelics—on learning and memory, having subjects perform various cognitive tasks while he scans their brains. When Doss had people under LSD perform real tasks—like watching a movie—their brain complexity went up, but so did the complexity of sober and alert brains also watching a movie. “If you match the mental activity,” Doss said, “the complexity looks the same.”

IF ENTROPY DOESN'T RELIABLY increase under psychedelics—or our tools aren't even measuring it accurately—then the explanatory edifice for the therapeutic efficacy of psychedelics begins to wobble. We're left without a full understanding of the network-wide effect that psychedelics have on the brain. Studies of “bad trips” during the psychedelic renaissance underscore the unpredictability of the drugs' effect and aftermath.

The inconclusive research into psychedelics also raises the provocative possibility that the brain might not be reorganizing itself in the way Carhart-Harris and others have suggested. Psychedelics may not be lifting us from ruts by dialing up neural chaos. The powerful experience may not be driven by entropy but by something far harder to pin down: the placebo effect.

Placebo is typically understood as the mind's expectation nudging the body toward healing. Simply believing that a treatment will work can activate real physiological responses, even when the treatment itself is inert. But drugs that affect consciousness, and psychedelics in particular, complicate this picture. What happens when the thing you're trying to heal *is* the mind? If someone expects relief and is then given a powerful hallucinogen that radically alters their consciousness, that expectation isn't just a subliminal hope—it becomes an overwhelming sensory and emotional reality. In that state, could the mind's belief in healing become even more powerful?

The powerful experience may be driven by something far harder to pin down: the placebo effect.

Boris Heifets, a Stanford anesthesiologist, has been on a quest to break down the elements of psychedelic experience. Determining the cause of an intense experience, he's reported, is not clear cut. "It is quite difficult to say whether a lasting change in mood or outlook was a result of the drug—a biochemical effect—or of the trip itself, the experiential effect," he told *Scientific American* in 2024.

Placebo is difficult to introduce in psychedelic experiments. If patients have, say, read Pollan's book or heard stories about the transformational effects of a psychoactive drug substance, they will have expectations of a similar experience, even if they know they may receive a placebo in their session.

Heifets got around that problem by conducting a clinical trial in which he gave ketamine (which has psychoactive effects) or a placebo to patients with clinical depression undergoing surgery for other issues.

Their expectant minds would be silent while they were under anesthesia and unconscious. Heifets's team found that changes in depression scores were statistically similar for the ketamine and placebo groups: The scores decreased for the placebo and ketamine group alike after surgical anesthesia. And these were large changes, cutting the depression scores by nearly 50 percent in both cases, and persisting after the operations, patients reported.

Heifets has also shown that patients experience a relief from depression and post-traumatic stress disorder from intense dream states induced by anesthesia. "Patients are having a very powerful experience," he's said, similar to ones reported by those who've taken psychedelics; again, without the drug.

Could it be that some kind of integration effort is the vessel where raw experience is distilled into lasting change? That after the profound experience, the real

improvements to mental health happen not because of the drug, but because of the mind's own work on itself? That psychedelics have clear and strong molecular effects is unquestionable; but to me, it's more likely the experience than changes in entropy that make this possible.

For months after that night in Joshua Tree, quarantined in the early days of the pandemic, I would notice strange new things. Shifting shadows, dancing dust motes, ghosts taunting my peripheral vision. They weren't distressing or startling; just little blips that tugged at my attention, as if my brain was still tuned to a different sensitivity, a heightened edge-detection filter no one had reminded it to turn off.

It didn't feel like some grand unlocking of consciousness, or a permanent new mode of being. It felt

small, subcortical almost: a tweak to a circuit, not a transformation of the self. And that, I think, is what science is telling us now, too.

Something is happening in the brain when psychedelics do therapeutic wonders. But it may not be what the theories have claimed. It may not be neural entropy, or predictive processing, or ego disintegration via control energy gradients. And yet when setting out with the intention to get better, people do, and often in profound ways. Maybe, for now, it's enough to say: Science doesn't quite know why. But for some, the experience is still worth the trip. 🧐

GRIGORI GUITCHOUNTS is a neuroscientist, AI researcher, and a senior associate at Flagship Pioneering, working on AI and machine learning.



The Hidden Landscape Holding Back the Sea

The fate of our planet's coasts rests on Antarctic bedrock

BY EVAN HOWELL

THE ICE IS MELTING. The seas, we know, will rise—slowly at first, and then suddenly. Locked within the West Antarctic Ice Sheet alone is enough ice to raise global seas some 16 feet. And some areas, particularly the East Coast of the United States, are set to see far more water than others. But the barrier between the present and the future does not lie at the surface, where sun meets ice. The boundary lies in the cold, hard rumpled Earth below. It is this landscape that determines where ice flows, where seawater can infiltrate, and, ultimately, when sea level rise will go from modest to almost unfathomable.

Once upon a time, what lurked under Antarctica's vast ice was unknown and, for all anyone could tell, unknowable. "We didn't even know if it was a single continent," says Martin Siegert, a University of Exeter glaciologist. Painting an intimate portrait of Antarctica's buried landscapes has been difficult, tucked as they are beneath up to nearly three miles of ice, in a harsh and unforgiving environment.

The first hints came from scattered rock outcrops and early drill cores. A handful of mid-20th-century geophysical surveys followed, and later radar began to sketch the shape of the land below.

As the picture sharpened over the decades, it revealed a hidden landscape of mountains, ridges, and canyons. And now, using massive troves of radar data and the fundamental laws of physics to divine what's under the ice, Antarctica is known to have geologic complexity as rich as any other continent on Earth.

But perhaps more than any other continent, its profiles foretell the contours of our own trajectory. Newly detailed maps reveal key vulnerabilities and chokepoints that protect the West Antarctic Ice Sheet's underbelly. Thanks to a few critical bumps and ridges, the edge of the ice sheet hasn't yet slipped deeper into the basin, where the bed slopes inland and retreat could run away. But when it does, the world's seas will rise swiftly.

IN 1912, BRITISH EXPLORER Robert Falcon Scott and his expedition, in a wretched retreat from the South Pole, perished on West Antarctica's Ross Ice Shelf along with 35 pounds of fossil-bearing rocks—a remarkable dedication to science, or perhaps the kind of dogged determination that gets you into such fatal predicaments in the first place.

Previous expeditions had gathered fossil plants from Antarctica (and survived), but Scott's team

Ice, at large scales, behaves in strange ways.

helped reveal traces of a broken-up supercontinent. Fossilized leaves from Permian swampy woodlands, or *Glossopteris* flora, matched specimens from surrounding continents. Aligned like jigsaw puzzle pieces, they revealed a broad swath of ancient forests—evidence of drifting continents, and decades later, the theory of plate tectonics. This was Gondwana, and its slow demise shaped Antarctica’s landscape and the ice it now holds.

Antarctica’s bedrock dates back more than 3 billion years, and its landmass has been incorporated into at least three supercontinents. Gondwana fragmented in the Jurassic 180 million years ago, with some rifting continuing to this day. Mountains rose as plates converged, and basins opened as they unzipped, at times forming shallow and warm carbonate seas. For impossibly long periods, the land simply eroded. Later, volcanoes spewed from a thin and rifted crust, not unlike North America’s Nevada looked some 17 million years ago.

Starting about 34 million years ago, ice spread slowly as the continent split from South America and drifted into polar latitudes. By 10 million years ago, spreading ice from eastern highlands filled West Antarctica’s rifted Gondwana basins, bowing down the land and creating unfathomable bedrock chasms—some reaching 8,200 feet below sea level.

East Antarctica, which lies primarily in the Eastern Hemisphere, is the stoic one—a mostly stable craton of primordial rock, resting high above the fray. Vast plateaus and the ice-obsured Gamburtsev Mountains mark its massive territory (which also includes the South Pole). Its ice sits perched above the sea and is relatively stable for now (the Wilkes Basin, lying below sea level, is one notable exception).

West Antarctica is another story. Separated from the eastern side of the continent by the Transantarctic Mountains, its crust is battered, rifted, and intruded with magma. Penn State glaciologist Richard Alley compares West Antarctica’s bedrock to the western U.S.’s Great Basin. Take a map of West Antarctica’s bedrock

and rotate it roughly 180 degrees (and squint): The features—lineaments, mountains, volcanoes, canyons, and swales—coarsely align. The geologic history is similar, too. Nunataks of the Transantarctic Mountains poke from the ice like a geologic cousin to California’s Sierra Nevada, which towers over Nevada’s tectonically stretched country. On the opposite flank, near Antarctica’s western coast, is a rough and “ratty” range—akin to Utah’s Wasatch Range.

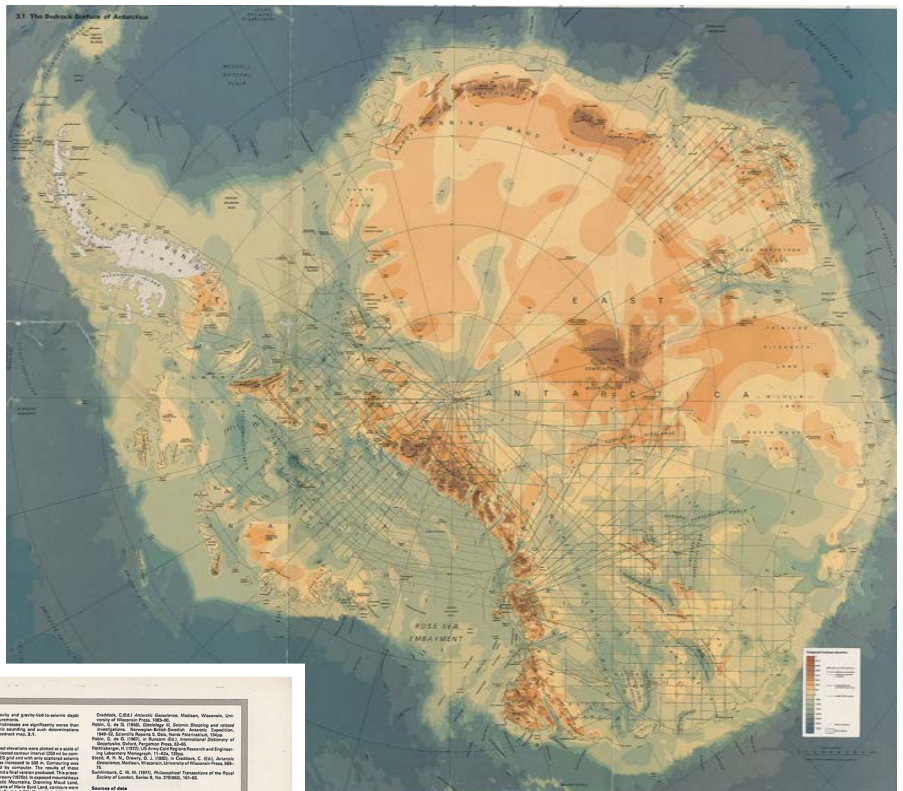
West Antarctica’s “marine grounded” ice reflects this restless foundation. Unlike its eastern counterpart, it rests in a deep bowl carved during Gondwana’s breakup, lying below sea level. It is the ratty range that is currently holding back the sea.

And this matters enormously. As warm ocean water reaches beneath floating ice shelves that fringe the continent, those shelves thin and weaken. This pushes the grounding line—the place where ice begins to float—inland into deeper basins, exposing more ice to the sea and triggering a runaway process of melting. If that happens, “The ice sheet collapses,” says glaciologist Frank Pattyn of the Free University of Brussels. “Every model shows that. It’s not rocket science.”

ICE, AT LARGE SCALES, behaves in strange ways, sometimes like a rock and other times more like a fluid, curving and bending over physical features.

Alley explains that, as snow accumulates year after year, it compacts into ice, eventually forming vast ice sheets that spread under their own immense weight. These ice sheets slowly ooze outward, cracking and bending as they flow around topographical features in long, finger-like glaciers that reach out toward the sea. From these glaciers extend colossal floating ice shelves, which also help anchor the glaciers behind them by lodging against rocky outcrops. On smooth surfaces, glaciers flow relatively unencumbered, like ladled pancake batter on a griddle. But on ribbed surfaces or tight valleys, it’s more like a waffle iron, pushing ice through narrow channels.

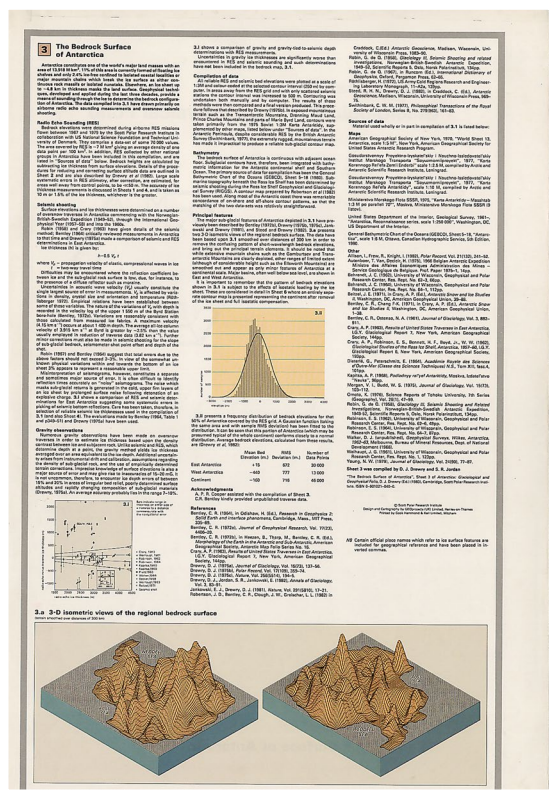
The first hand-drawn, continent-wide Antarctic bedrock maps by the *Glaciological and Geophysical Folio*, released in 1983. These maps were the first attempt to reveal the shape of the bedrock below the ice, but they could not be directly fed into computer models.



All is well so long as interior snowfall keeps pace with ice loss along the seaside edges. But in West Antarctica, the waters are winning.

Warm ocean waters once stayed away, but those days are gone. The now-warmer sea circulates beneath those floating ice shelves, thinning them from below. And along key West Antarctic glaciers, only a few minor ridges act like natural seawalls or anchors, separating the ocean from the continent's thick grounded ice. "If it gets there, we're going to see a lot of sea level rise pretty fast," says Alley.

Imagine the fate of Miami's famed beaches resting on Antarctica's bedrock—its rock type, density, shape, and dip. How slippery or lubricated is the rock surface? What about the meltwater drainage system—rivers, streams, lakes—that flow in this cold, cavernous world? ("If you take a piece of ice and put it on a table, it's not going to move. You put a little water on it, it's going to slide," says Robin Bell, a geophysicist at Columbia University.)

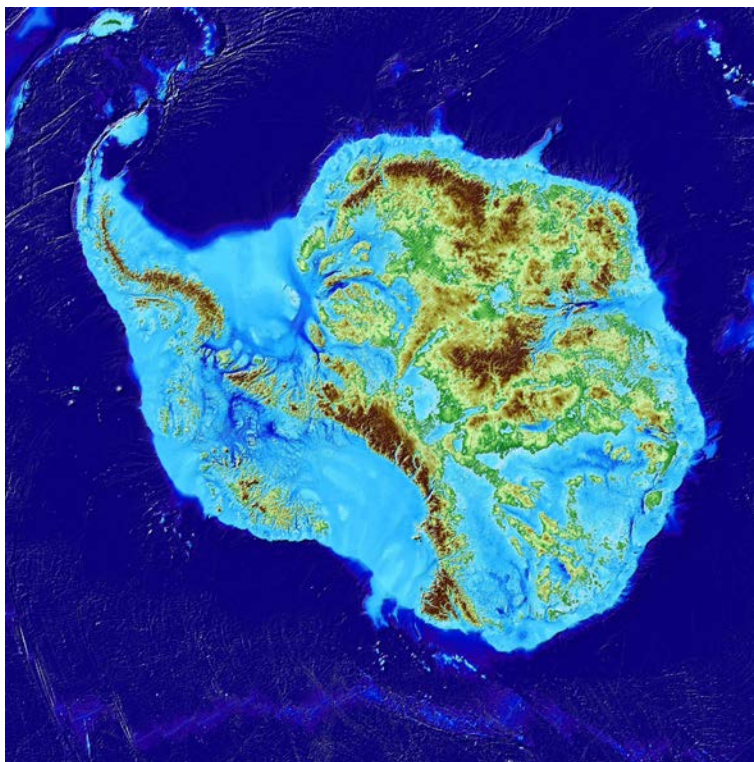


Now consider the bewildering complexity of rock, ice, and water—each with its variable and heterogeneous properties. Scientific modelers trying to understand the planet’s future must take all of that and boil it down into something clean enough to feed into mathematical equations and computer code. As statistician George Box wrote in 1987, “All models are wrong. Some models are useful.” And useful ice sheet models need reliable bedrock maps.

UNTIL THE MID 20TH CENTURY, scientists had only sparse outcrops and vague hunches upon which to hypothesize about Antarctica’s bedrock. Scattered seismic lines, processed sound waves through the Earth, revealed two-dimensional grainy glimpses of the land below, but these surveys were few, far between, and required drilling through more than 160 feet of soft surface snow. Radar—or specifically, radio-echo sounding—blew it wide open. Deployed in the late 1960s, this technique didn’t require drilling and could collect data on moving platforms. With sensors soon mounted on U.S. Navy long-range Hercules C-130 transport planes, data came rolling in.

The leap forward was staggering, says Siegert: a five-fold increase in data acquisition. Yet, scientists still had only a “patchwork quilt” of ad hoc surveys, conducted at different times and with varying systems. An effort to systematically survey the continent with standardized techniques began in the late 1970s but soon waned.

After all, in a place this unforgiving, surveying flights are limited, and each can produce only a thin ribbon of radar data directly beneath its path. “It’s like trying to reconstruct the nation’s landscape from I-80 across New Jersey,” says Alley. “We have a few places with spectacular, wonderfully fantastic data,” he says wide-eyed, adding, “But we also have big gaps.” For decades, radar flights have largely buzzed the continent’s western edge, and for good reason: That’s where the threat is greatest.



Glaciologists badly needed compiled maps to understand the evolving ice sheet. The first hand-drawn, continent-wide bedrock maps, *Glaciological and Geophysical Folio*, released in 1983, were “lovely, aesthetic” maps, says Siegert—ones that might today look handsome framed on a study’s wall but couldn’t be directly fed into computer models. That changed when an international effort led by the British Antarctic Survey released Bedmap in 2001, a continental-scale gridded product. But in terms of data quality, Siegert explains, the map wasn’t much of an improvement on the hand-drawn 1983 effort. Bedmap2, released in 2013, benefited from a much larger trove of data, offering a far sharper picture of what lay below. But huge swaths of Antarctica were, and still are, unexplored by radar flights.

Peter Fretwell, a geophysicist at the British Antarctic Survey, says the Bedmap team takes an “uglier but honest” approach to interpreting across gaps, honoring every datapoint and making geologically informed assumptions between them.

FILLING IN THE DETAILS BedMachine, available from the National Snow & Ice Data Center, reveals the hidden landscape beneath Antarctica's ice. Both BedMachine and Bedmap—gridded models built from extensive radar surveys—map Antarctica's bedrock at 500-meter resolution. While West Antarctica's vulnerable marine-based glaciers have been well covered by radar flights, large parts of the continent rely on interpolation where no direct data exist.

Dartmouth College glaciologist Mathieu Morlighem, the mastermind behind a product called BedMachine (released in 2020), took a different approach. He read between the lines with fundamental physical laws—primarily the conservation of mass. While satellites can't penetrate the ice to reveal bedrock topography, they show the ice surface—every bump, crack, and even ice speed—with remarkable clarity.

In a “eureka moment,” Morlighem and his team rearranged equations to compute ice depth in unmapped regions, mathematically rendering the bedrock topography from the known surface shape and speed, or ice flux. This wasn't just a slight improvement: BedMachine exposed never-before-seen valleys and mountains. It revealed the Denman Glacier in East Antarctica to be resting on the deepest point ever mapped on land, reaching some 11,500 feet below sea level. Even Fretwell concedes wryly that BedMachine is “much better where we don't have data.”

These two mapping products aren't in competition. Those trying to understand the paths and fate of Antarctic ice are keen to use all the information available. Following the release of Bedmap3 earlier this year, the teams hope to combine their efforts—each offers 500-meter pixel resolution (for comparison, Google Terrain View often features 15-meter pixel resolution of land not covered in ice). But as Pattyn puts it, “the devil is in the details.”

ENORMOUS AND CONCERNING GLACIERS, like Thwaites and Pine Island, flow relentlessly toward the Amundsen Sea in West Antarctica. But they are traveling across the Gondwana topographic grain—an ancient wood-like pattern of ridges and troughs carved into the crust during the supercontinent's

breakup. Farther inland, a smoother path leads through deep valleys toward the Ross Ice Shelf, but that's some 900 miles away. Even ice likes shortcuts. Instead, Thwaites—roughly the size of Great Britain—squeezes through a narrow stone bottleneck along a more direct path.

For now, the floating ice shelves brace the great glaciers and slow their flow. But if the shelves disintegrate—as happened with the rapid and unexpected 2002 breakup of the Larsen B ice shelf—the buttressing disappears. This means the glaciers move faster toward the sea, and the ridges alone may not be enough to hold them back. Meanwhile, the grounding line—where the ice begins to float—creeps inland into the deeper basin where fewer topographic bottlenecks exist. “We need to beat the heck out of understanding that bottleneck,” says Alley.

For some researchers, that means renewing the systematic, continent-wide survey that stalled decades ago. Technology is helping, too. Newly deployed swath radar technology offers a twist on the old technique, enabling, as the name suggests, much wider glimpses beneath each flight's path and immediate three-dimensional renderings that are “so fantastic it's hard to imagine,” says Alley. But everyone agrees on the urgency, because nature waits for no one.

And many U.S. shores will be among the worst impacted. Seas don't rise uniformly like water in a bathtub and will instead creep faster and higher along the Atlantic seaboard and Gulf Coast, into Manhattan's financial district, swallowing North Carolina's Outer Banks, and leaving Florida but a sliver. Some places will fare worse, some better. Few doubt these outcomes—the tension lies in *when* sea level rise goes from gradual to drastic.

If all of Antarctica's continental ice vanishes, seas could rise an average of 190 feet above where they lap today. And if it does, the bedrock will be laid bare, its canyons, mountains, ridges, and swales. Something old, something new. 🌀

EVAN HOWELL is a Colorado-based freelance science journalist. His work has appeared in *Science*, *Scientific American*, *Science News*, and other outlets. Evan holds a master's degree in geology and spent over a decade working as a senior geologist.

We Might Not Be So Strange

Perhaps intelligent life wasn't so unlikely after all

BY PHILIP BALL

TIMING MAY, ULTIMATELY, be everything. It seems a rather odd coincidence that in the 4.6 billion years since Earth formed, humans have emerged now. For us to be here, first life itself had to get started, of course, and then develop more complexity. Then enough oxygen had to accumulate in the atmosphere. And habitability had to continue for a further 2 billion years or so while complex animals evolved. But here we are, now, thinking about such things, on a world that seems uniquely hospitable to us.

Good thing it didn't take too much longer, however—for in around 5 billion years' time, the sun will start to run out of fuel and will swell and fry the Earth, before shrinking to a much-cooler white dwarf. It's hard to imagine any kind of life surviving that.



Why didn't we appear on Earth much sooner?

The odds of all of these things lining up to allow intelligent life to evolve on the same kind of timescale as the life of our planet—neither much sooner nor much later—seemed vanishingly small in the late 20th century to theoretical physicist Brandon Carter.

Scientists had been bandying about the question of whether complex life exists elsewhere since even before it was famously posed by the Italian physicist Enrico Fermi in the 1950s (“Where is everybody?”). But at a Royal Society meeting in London in 1983, Carter, who had studied alongside Stephen Hawking at Cambridge, presented a new way to think about that problem in a talk on “The anthropic principle and its implications for biological evolution.”

The presentation, to luminaries that included Hawking himself and Nobel laureate Steven Weinberg, came at the end of a long day and, as cosmologist Paul Davies, now at Arizona State University, remembers it, was not the most engaging of talks. Carter “over-ran by many minutes,” he recalls. “His overhead slides were incomprehensible. I remember thinking ‘Whatever is this all about?’”

But what ultimately sunk in was that Carter was offering an argument for why beings as cognitively complex as us are likely

to be very rare indeed in the cosmos. Even if we are not truly alone, he implied, the chances of other intelligent life forms are so low that we might as well be. “The essence of Carter’s coincidence is that humans evolved on a timescale approaching Earth’s total habitable lifespan—we have evolved close in time to the ultimate extinction of all life on Earth,” says geomicrobiologist Daniel Mills of the Ludwig Maximilian University in Munich.

So what? Well, the apparent coincidence has three possible explanations. One is that the two phenomena really do have inherently similar timescales. But there seems to be no logical reason why they should, because they have nothing to do with one another: One timescale is determined by stellar physics, the other by biological evolution. A second is that the evolution of intelligent life is typically much faster than it was on Earth, but for some reason it took an unusually long time here. But, again, there’s no obvious reason why that should be so.

The third possibility is that the appearance of human-like intelligence on a habitable planet is usually slow compared to stellar lifetimes, and so on most planets it never gets the chance to happen. We just got lucky.

Lucky how? Carter argued that, in order to reach human-like intelligence, life here had to clear several hurdles that involve rare, chance events: a gauntlet of “hard steps” along the way. These hard steps are “evolutionary singularities,” leaps that occurred perhaps only once. Otherwise, they wouldn’t be hard. (The evolution of the eye, for instance, can’t be one, as it is thought to have occurred many times independently in various species.)

Carter proposed two candidate hard steps. First, the origin of the genetic code (by means of which DNA sequences can encode proteins). Second, what he called “the final breakthrough in cerebral development,” meaning the appearance of human-level cognitive capabilities, such as language. Other researchers have since suggested other hard steps, including the origin of life itself (abiogenesis), oxygen-generating photosynthesis, the appearance of eukaryotes, and animal multicellularity.

Carter’s “hard steps” picture remains a pervasive and influential framework for thinking about intelligent life beyond Earth. Earlier this year, though, a team of scientists challenged his argument for why the evolution of intelligent life is cosmically unlikely.

Mills and colleagues took these last four steps, as well as complex cognition, as the best “hard steps” candidates—and considered how unlikely each of them *really* are. Their conclusion: Perhaps none of them are. “We are raising the possibility that hard steps do not exist at all,” Mills says.

Maybe, they say, the emergence of beings like us is then not hindered by hard steps but is simply slow. Perhaps the universe is teeming with alien civilizations—or will be before very much longer. Whether you find that reassuring or unsettling might depend on which sci-fi movies you’ve watched, but the new work is making some think again about the course of evolution on our planet.

ONE PROBLEM IN DETERMINING the likelihood of a given evolutionary step is that, of course, we only have one example to study: the trajectory of life on Earth. And even here we have a very incomplete record of all things that ever lived: Evolution has a high rate of information loss over geological time.

For example, a transition such as the appearance of photosynthetic, oxygen-making bacteria might not have been truly unique but only looks that way now because only the ancestors of one of several such events have survived or left any traces. Alternatively, two such events might have happened independently in closely related lineages that subsequently became genetically indistinguishable enough that they look now like a single event.

Mills and colleagues say that the first such scenario—multiple occurrences of which only one left a trace—might have happened for the appearance of eukaryotes (cells with a nucleus, distinct from bacteria). Some fossil records of single-celled organisms from the Proterozoic era 2.5 billion to 0.54 billion years ago (during which eukaryotes are thought to have arisen) look kind of eukaryotic but can’t be definitely ascribed to the lineage of today’s eukaryotes. They might in fact be the traces of entirely independent eukaryote-like fusions of simpler cells—in which case, far from being rare, such events could have happened several times.

What’s more, just because we now see only one instance of a key evolutionary transition doesn’t mean it was an unlikely event. Evolutionary biologists have long also recognized a winner-takes-all aspect in evolution: The first lineage to make a particular innovation may lay such tenacious claim to the evolutionary niche it opens up that other lineages never get a chance to compete. Mills explains: “The first evolutionary lineage to successfully complete the transition in question is the one that ultimately endures.”

Life began almost as soon as the environment became conducive.

Take phototrophic bacteria. These convert light energy into chemical energy, the first step toward oxygen-producing photosynthesis. There are two groups of phototrophic microbes today, which use different light-absorbing molecules and two different gambits for making the process efficient. Between them, these two groups might have basically cornered the market, leaving no options for other potential phototrophs to seize. It's possible that human-like cognition involved such a priority effect, too.

In such ways, evolution pulls the ladder up behind it: By its very occurrence, rather than by its inherent improbability, a major transition limits what can come after it. Most organisms today had better be able to cope with an oxygen-rich atmosphere, for instance. Once a step is taken, there's no going back—and so it looks as though the step is intrinsically unique and unlikely, merely because it happened at all.

Mills and colleagues say these two illusions might apply to all the candidate hard steps.

"I think the case is far from proven either way," says Davies, "but I do like how Mills and colleagues discuss the ways that apparently singular evolutionary events may appear intrinsically improbable, even though they are not."

IF MILLS AND COLLEAGUES are right that there are indeed no truly hard steps to intelligent life, then why didn't we appear on Earth much sooner? Why have we only arrived

about halfway before the inevitable end of our planet's habitability?

The researchers say this need be no mystery. "It is not hard at all for deep-time paleontologists, geochemists, and Earth system modelers to think of reasons why our arrival could have been so 'greatly delayed,'" they write. While it's tempting to think of the key evolutionary steps as being all about biology, in fact they could only happen when the environment itself was permissive. It's not that the crucial steps were hard in themselves but that they had to wait until the time was right.

The final three candidate hard steps, at least here on Earth, required an oxygen-rich atmosphere. But of course life doesn't simply adapt to a pre-existing environment. Rather, life and environment coevolve. We are adapted to breathe oxygen not because the Earth's atmosphere was inherently oxygen-rich but because earlier living organisms made it that way. This coevolution of the biosphere and its environment was advocated in the Gaia theory of British scientist and inventor James Lovelock. "Lovelock's fundamental insight," says marine and atmospheric scientist Andrew Watson of the University of Exeter in the United Kingdom, who was not involved in the work, "is that Earth history is a co-production between the environment of the Earth's surface and the life developing on it."

Obviously humans need oxygen—but in fact we need it at a concentration that, according to the geological record, wasn't

established stably until about 400 million years ago, in an episode known as the Paleozoic Oxygenation Event. In other words, says Mills, “for over 90 percent of Earth’s existence, oxygen levels in the atmosphere were likely too low to support long-term human settlement.” And once the atmospheric conditions were right, it only took hundreds of millions of years for humans to appear, not billions. “So, relative to the onset of the permissive conditions, the origin of humans was relatively quick,” says Mills.

The other two most recent candidate hard steps on Earth—animal multicellularity and the appearance of eukaryotes—also demand a fair amount of oxygen, because they force cells to burn up a lot of energy. It’s not easy to figure out exactly what the threshold oxygen concentration was for multicellular life here. But it seems likely to have been higher than the level that existed before the so-called Great Oxygenation Event (GOE) of around 2.4 billion years ago, when oxygen went from being a mere trace gas in the atmosphere to comprising about 1 percent of it (likely thanks to a combination of photosynthetic microbes and a shift in the way oxygen reacted with the planet’s surface environment).

So for at least half of Earth’s history, the three final putatively “hard” steps were out of the question anyway, simply because the environment wasn’t right. “I agree that the basic hard-steps model doesn’t take into account the delays that might be inherent in the evolution of the Earth system,” says Watson. He has previously pointed out that eukaryotes seem to have appeared rather soon after the GOE, suggesting that the event responsible for them wasn’t so inherently unlikely once there was enough oxygen around.

What about the earliest two candidate hard steps? Little is known for sure about the origin of life, but one thing seems clear: It likely couldn’t have happened during most of the

Perhaps the emergence of life was neither hard nor improbable after all.

Hadean era, the period up to around 4 billion years ago. For much of that time, the Earth was still seething with volcanism from the fury of its formation, and was strafed by giant meteorites, the debris left over from the formation of the solar system. For most of this time, the planet would have been too hot to host substantial bodies of water on its surface.

Some think that the Earth would have been inhospitable until about 3.9–3.7 billion years ago, the age of the earliest fossil evidence for primitive life. But recent work to reconstruct the last common ancestor of all life on Earth today, based on comparisons of their genomes, has suggested this ancestor might have been as old as 4.2 to 4 billion years. That would imply that life began almost as soon as (if not indeed apparently before!) the environment became conducive. Perhaps the emergence of life was neither hard nor improbable after all.

As for the origin of photosynthetic bacteria: Today’s cyanobacteria can’t survive in water warmer than about 163 degrees Fahrenheit, and it might have taken a long time for the Hadean seas to cool to something close to that temperature.

You just can't rush something like us.

All in all, then, Carter's puzzle—why have we turned up so late in Earth's history—needn't imply a solution involving improbable bottleneck events that don't happen on most Earth-like planets. Rather, you just can't rush something like us. Our planet needed billions of years before it could become human-friendly. "Intelligent life could require much less time on other planets that are able to achieve permissive conditions more quickly," says Mills.

Michael Wong, an astrobiologist at the Carnegie Institution for Science in Washington D.C., thinks that the researchers "don't make a slam-dunk case" but that their analysis is "probably as good as one can do right now."

"I am quite sympathetic to this reasoning that we can only understand the timing of these key inflection points through the coevolution of our biosphere, geosphere, hydrosphere, and atmosphere," Wong says. "Planets change, and the probability of the emergence of something [on them] is not uniform throughout a planet's history."

ADMITTEDLY, IT DOES rather *look* at the moment as though we are a solitary outpost of intelligence floating in an inhospitable

cosmos. Decades of searching for signs of intelligence far afield in our galaxy have consistently elicited nothing but what some scientists call the Great Silence.

Others might reply that this is a classic case where absence of evidence is not evidence of absence. The silence is hardly surprising given that we don't really know what we should be searching for, we've been searching for barely a blink of cosmic time, and there's a *lot* of space to cover. Maybe it's just too early to conclude anything at all about the chances of intelligent life on other worlds from our quest so far to find it.

Carter appeared to give reason to think that the search for extraterrestrial intelligence is doomed from the outset. But the not-so-fast response of Mills and colleagues is, they say, a potentially testable idea. For one thing, they argue that we need to develop a better understanding of how the candidate hard-step evolutionary transitions actually happened, being open-minded about how unique they really were. This includes getting a better understanding of the environmental conditions, such as oxygen levels, temperature, ocean acidity and salinity, and so on, needed for these steps to be possible at all.

“We have no idea how non-life became life.”

But perhaps the most discerning test will be what we find in the atmospheres of planets orbiting other stars, some of which can now be studied by astronomical instruments such as the James Webb Space Telescope.

For example, if the development of oxygen-producing photosynthesis was truly a hard step, we’d be unlikely to find Earth-like exoplanets with significant amounts of oxygen in their atmospheres. Some astronomers say that we might even read the signature of intelligent life in alien atmospheres, for example if they contain relatively high concentrations of complex gases such as chlorofluorocarbons, for which no known natural source exists.

If Mills and colleagues are right, says Watson, “then when we are able to spectrally analyse exoplanet atmospheres, there is a good chance of detecting relatively modern Earth-like biosignatures.”

That time might not be very far off. In early 2025, a team from the University of Cambridge in the U.K. claimed (controversially) that they had detected the fingerprint of a compound called dimethyl sulfide, made naturally on Earth only by living organisms such as marine plankton, in the atmosphere of a planet called K2-18b orbiting a star 120

light-years away. More certainty about such claims might have to await better instruments. “I look forward to the day we build and launch telescopes that can get us the answer,” says Wong.

While the researchers’ arguments pose a challenge for most of the putatively hard steps, the biggest unknown, Davies notes, is the first: the genesis of life itself. “We have no idea how non-life became life, how many steps were involved and what the prevailing conditions needed to be,” he says. “And you can’t estimate the odds of an unknown process. This is in contrast to all the subsequent putatively hard steps, because at least we know the process involved: Darwinian evolution. Nobody knows the process whereby non-life became life.”

For this and other reasons, Watson thinks that Carter’s notion of hard steps might still hold—even if the slow pace of environmental change puts the brakes on how soon intelligent life can arise. In a forthcoming paper, he presents a model in which such delays are incorporated into Carter’s earlier picture. “The hard-steps model remains a useful and viable framework for understanding the evolution of complexity in the Earth’s biosphere,” he says.

“If I’m right, we will find only Archean-like biosignatures [in exoplanet atmospheres],” says Watson. “Sometime this century, we should find out who is right.” ☺

PHILIP BALL is a freelance writer based in London, and the author of many books on science and its interactions with the broader culture. His latest book is *How Life Works*.

Why I Became a Birdwatcher

Learning to look past indifference and into the mystery of life

BY ADAM NICOLSON

THE FIRST TIME I MET A BIRD close-up, it was dead. A raven. Even seeing it on the side of the mountain road in Crete was a shock: a large, dark splayed body the size of a small dog. I stopped the car and got out, not quite certain if I would find a wounded animal, enraged at its fate and frenzied in pain. But it was properly dead. Whatever it had once been had left. Holding its rigid form—all looseness and flexibility gone; it was as stiff as a dried cod—feeling my way around it, rustling open its wing feathers, pushing through the soft plumage on its nape and back, was like exploring a derelict house. Rafters, furnishings, upholstery, timbers, abandonment. It had been shot and its bill was bloodied in gouts toward the point, yet the midnight blue of its back and wing shimmered in my hands, each sheathing layer overlapping the next in soft-edged scales.

The bird felt like a miracle of construction: the splitting-axe of its bill, more paleo than any piece of bird-body I had ever seen, capable of crushing the skull of a rabbit in one slow, final closure; the nape that it ruffles and raises in both anger and desire; the spread of the primary feathers in the wing, no matter wasted, each rib as structural as a medieval vault, as fine as necessary, graded in width and strength from outer to inner and from tip to root.



I have come to think that the inaccessibility of birds is the heart of their marvelousness.

And then the claw, dirty from life, knobbled like a Malacca cane, the darkness giving way, as an undertaker's shoe might when muddled beside the grave, to a leathered practicality, armored against the world and padded against rock.

The dead bird was not the bird. The body seemed only to have been the means by which the bird could have become itself. But that moment of closeness to such an animal was the beginning of something for me.

I had never paid much attention to birds. For whatever reason—perhaps because everyday birds were too small, too evasive, too difficult to know, requiring too much patience and too much submission to their ticky little habits—I had not cared about them. Or not bothered to care.

My family had never been troubled by them. My father—no naturalist—was always more interested in looking across a bit of country than in what it might be made of. The view was the thing, not the plants or animals in it. As a boy I never chose to understand the birds or tried to learn the songs or calls. I did love seabirds—big, obvious, loud, heraldic, unmistakable—and came to know them on our annual holidays in Scotland, but the birds in the wood or the garden at home remained a blank, a flicker of nothing much, like motes in sunlight.

Why this indifference? Perhaps because attending to the birds seemed marginal to the bigger stories. Perhaps because my father looked down on anything like that. He built himself a gazebo—an 18th-century joke: “I will gaze,” as a fusion of Latin and English—on the corner of the garden from which he could survey a stretch of country “unchanged since Jane Austen saw it,” as he would often say.

A view, or a landscape as it was always more grandly described, precludes a love of anything else and as the naturalist Mark Cocker described in *Our Place*, his excoriating 2018 account of the failure of modern nature organizations to attend to the well-being

of nature, this view-addiction has presided over a destruction of everything else. Perhaps because of an inherited taste for parkland, carpet has seemed better than vitality, smoothness than mess. The Britain Cocker portrayed has fetishized a “landscape beauty almost devoid of biodiversity ... Nature is slipping away from these islands ... Not since the last ice age has Britain been so stripped bare of its natural inhabitants.” In common with that presiding culture, I had walked thousands of miles across a diminished Britain without ever truly recognizing what was or wasn't there.

Later, when I encountered bird people who had spent their years of apprenticeship learning and attending to the birds, I slid past them. I remember in Turkey, making a radio program on Homer with my friend and lifelong birder Tim Dee. As we stood together on the Trojan plain, perched on the slopes of a Bronze Age tumulus known as the Tomb of Achilles, he said he could hear a woodlark singing above us. I began to talk into his woolly microphone about the beauties of that place, its oak woods, its leaning, creaky olive groves, the lionskin of late-summer grasses, the endless, homeless north wind blowing across from the steppes, and said something about “the song of a lark high above us.” Tim stopped me: “Not a lark, a woodlark.” He can never watch a film without agonizing over the presence of the wrong birds at the wrong time of year on the soundtrack.

We started again and I said “lark” again and I remember his frustrated, raised eyebrows and the pursed lips of the radio producer who remains silent, his eyes on the horizon, as his contributors mouth idiocies.

It is a reproachful memory, symptomatic of a certain frame of mind. And so a couple of years ago I decided to embark on an attempt to encounter birds, to engage with a whole and marvelous layer of life that I had lived with in a kind of blindness and deafness for decades.

I wanted to look and listen, to return to Bird School and see what it might teach me. I knew it would be long, slow and bitty. Birds don't easily offer themselves up and in that way differ from our modern experiences in which the wanted or desired is almost constantly available. Birds move too fast or are too far away. We summon their alarm. Their concealment is occasionally interrupted only by a flickering, transient, uncertain presence. "Nature likes to be hid," Heraclitus wrote in Ephesus 2,600 years ago and as such birds are the opposite of a landscape view that lays itself out in a kind of horizontal, placid seductiveness. Birds refuse that subjugation. They are often on the run, intent on a life in which the human observer is merely a threat or annoyance. They know how to fly away, neatly like owls or buzzards, with a kind of disdainful calm, or like pigeons with a grand fluster of feathers and noise, or blackbirds with a car-alarm-disturbed-terror-shriek; or to hide and creep, to stay still and silent, like the snipe or woodcock in the most anxious stillnesses in nature, to warn each other of some alien mammal in the neighborhood and to observe us far more than we ever observe them.

Experiments have shown how much they dislike the threat that a human eye represents. They don't like being looked at, and birds, if you look at them too hard, will fly away. The eyespots on butterfly wings are designed to alarm bird predators and the reaction of most birds, especially in the young, is to take flight. The response is more powerful when it is a watching face; a pair of eyes is more frightening to them than a single eye-shaped form and one can experiment with this: Watch with your hand over one eye and the birds might be untroubled. Remove it and they will flee. Deep in their adaptive minds is the knowledge that predators have their eyes in the front of their heads, giving them the necessary, wide, binocular gaze, and it is that double, watching, hungry vision that birds fear and avoid.

We bring terror in our wake. Charles Foster, the English writer on the wildness of animals, has said that whenever he wanders into the section of a bookshop called "Birdwatching," he looks for those books that

The dead bird was not the bird. But that moment of closeness was the beginning.

might describe or try to describe the experience of birds watching us.

What do they make of us? What is that large mammal that likes to stop on its walk through the wood and somehow transform its little eyes into a pair of bug-eyed predatory lenses with which it tracks us as we pass?

Could we ever trust it? What is its world, its intention? What does it want?

I have come to think that the inaccessibility of birds is the heart of their marvelousness. Both concealment and their capacity for distance and height is their form of pride. We do not own them. They possess themselves, even as their indifference makes us long for them. "You don't hear birds, you hear worlds," Olivier Messiaen, the great French composer, once wrote. That unknowable otherness, the way in which they represent the complex, involved presence of entire life systems that are not-us but are somehow interleaved with our own, is the source of the birds' beauty. They are unknowability itself alive in front of us, colored, feathered, voluble, quick, inaccessible, with something fractal about them, so that the more you look, the less you know. Or perhaps the more you look, the more you know how little you know. You can only be led toward them, as if into a mystery. ☺

ADAM NICOLSON is the author of many books on history, landscape, and great literature. He is the winner of the Somerset Maugham Award, the W. H. Heinemann Award, and the Ondaatje Prize. His books include *The Life Between the Tides* and *Why Homer Matters*. He lives on a farm in Sussex.

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Our Dark, Unvaccinated Future

Diseases that cause suffocation, paralysis, and childhood death are poised to come surging back

BY MEGAN SCUDELLARI



ON THE FINAL NIGHT of her pediatric residency in the mid-1970s, physician Kathryn Edwards stood by the bedside of a dying toddler. A bacterial infection, *Haemophilus influenzae* type B or Hib for short, raged through the young girl's bloodstream, inflaming the membranes around the brain and spinal cord. That night, realizing a vaccine could have saved the child's life, Edwards resolved to devote her career to developing vaccines for children.

Vaccinations in the U.S. would plummet. Death, illness, and disability would surge.

In the 1970s and '80s, 20,000 children younger than 5 became infected with invasive Hib each year in the United States, and about 1,000 died. In 1987, the introduction of an effective Hib vaccine soon dropped those numbers by 99 percent, down to single digits per year, the cases almost exclusively occurring in unvaccinated or undervaccinated children.

But today, more than 45 years after that terrible night, Edwards fears that the pre-vaccine era could return. “We are in a very scary time,” says Edwards, an expert in childhood respiratory disease and vaccine safety who recently retired from Vanderbilt University Medical Center. “We have to realize these diseases are the bad ones. We really don’t want them to come back.”

But they are back. Diseases that the U.S. had all but eliminated decades ago through mass vaccination campaigns have returned. Measles is surging and whooping cough is close on its heels, with cases tripling in many states over the past year. That’s an ominous trend, says Amy Edwards, an associate professor of pediatrics at Case Western Reserve University School of Medicine. “When you see whooping cough on the rise and measles on the rise, you know the vaccination rate is high but dropping. Then come the rest.”

“The rest” is a long list of names that were once destined for the dustbin of history—polio, diphtheria, Hib disease, rubella, and more—each accompanied by horrible complications, including blindness, brain injury, paralysis, and life-long chronic illness and disability. “We have tens of thousands of history and medical books that describe the horrors of some of these diseases,” says Daniel Pastula, chief of neuroinfectious diseases and global neurology at the University of Colorado. “And we don’t see them anymore because of vaccines.”

Vaccines protect both the vaccinated individual and the population at large, because if enough people are immune to an infectious disease, that contagion cannot easily spread from one person to another. Yet vaccination rates that began declining during the COVID-19 pandemic have continued to drop, putting the population at risk for the resurgence of these illnesses. But how quickly could that happen, and what are the most pressing dangers?

Through discussions with doctors, infectious disease scientists, and public health officials—including some who witnessed the damage wrought by these illnesses before vaccines were available—*Nautilus* explores what could happen next, and how it might be prevented.

We've reached a pivotal point in this cascade of returned diseases.

CASCADING CONTAGIONS

Declining vaccination rates might paradoxically be a consequence of vaccines' incredibly successful and safe track records: Most people alive today have no first or even secondhand experience with many of these illnesses. But other factors are also at play, including vaccine hesitancy fueled by rampant vaccine misinformation.

Additionally, work by the current U.S. Secretary of Health and Human Services, Robert F. Kennedy Jr., to rewrite decades of vaccine policies is actively changing the landscape of vaccine availability and access. For example, experts interviewed for this article unanimously expressed support for—and fear of losing—the Vaccines for Children Program, established by Congress in 1994 to provide vaccines to low-income children at no cost. That program alone distributes more than 70 million pediatric vaccines each year and is estimated to have prevented 508 million illnesses, 32 million hospitalizations, and saved more than 1.1 million lives since its inception.

The program is funded and run by the U.S. Centers for Disease Control and Prevention (CDC), which has experienced major funding

cuts and layoffs under Kennedy's supervision. It covers the cost of vaccines recommended by the Advisory Committee on Immunization Practices (ACIP)—a body that Kennedy gutted in June and filled with his own appointees, some of which have expressed vaccine skepticism. If the administration or ACIP were to restrict or abolish the Vaccines for Children Program or the vaccines it offers, vaccinations in the U.S. would plummet. Death, illness, and disability would surge.

Already, vaccination rates in the U.S. are dropping. Declines in vaccination began during the pandemic, when social isolation and disruptions in healthcare coverage led to fewer people being vaccinated for a host of diseases those years. But even as the pandemic ended, vaccination rates continued to decline. In the 2024-2025 school year, for example, record numbers of unvaccinated children entered schools: More than 280,000 kindergarteners in the U.S. did not complete the measles, mumps, and rubella (MMR) vaccine series. Compared to the year before, exemptions from one or more vaccines among kindergartners increased in 36 states and D.C., with 17 states reporting exemptions

exceeding 5 percent. And there is no end in sight. In early September, Florida's surgeon general announced that the state planned to end all vaccine mandates, including those for schoolchildren.

If vaccination rates continue to drop, eliminated diseases will come roaring back. First to return: measles.

MEASLES

Measles is one of the world's most contagious diseases. It is especially dangerous for young children and people with weakened immune systems, and the complications are severe, including deafness, blindness, and brain damage. Additionally, measles poses a unique threat to the immune system: Like a guided missile, measles virus specifically targets immune system cells responsible for remembering past illnesses. So following measles infection, an individual's immune system has severe amnesia for two to three years, with little memory of how to protect itself from common pathogens. This, in turn, leads to an overall higher risk of death from other infections.

In 2000, the World Health Organization declared the U.S. measles-free, but the tide quickly turned. Since 2019, MMR vaccination rates have declined annually nationwide. As of September 3, more than 1,431 measles cases have been reported this year—more than any year in three decades—and with four months still left in 2025. Cases are rising so quickly, in fact, that earlier this year, the Johns Hopkins Bloomberg School of Public Health and the International Vaccine Access Center released a U.S. Measles Tracker—a mapping tool that is eerily reminiscent of COVID-19 trackers during the pandemic.

"We're really on a tipping point for measles," says Nathan Lo, an assistant professor of infectious diseases at Stanford University. "It is already at risk for returning to become a commonplace disease." At current vaccination levels, measles will become endemic—that is, consistently present and circulating in the U.S. population—in 25 years, resulting in more than

850,000 cases and 2,250 deaths, according to an April modeling study from Lo and Stanford epidemiologist Mathew Kiang. If there is a 10 percent decline in vaccination rates, measles could skyrocket to 11.1 million cases over the next 25 years. And if there were a dramatic 50 percent decline, measles would be endemic in just 5 years, with 51.2 million cases over a 25-year period.

WHOOPIING COUGH

Whooping cough, also called pertussis, is another vaccine-preventable disease that's been raging back: As of Aug. 23, 2025, there have been 19,159 reported cases of pertussis in the U.S. this year—almost 2,000 more than the same period last year, according to the CDC. At this rate, the U.S. could reach 70,000 pertussis cases by the end of the year, according to one recent prediction.

Pertussis, with its uncontrollable, violent coughing, is likely to spread quickly because it is almost as contagious as measles. Protection against pertussis from a combination vaccine against tetanus, diphtheria, and pertussis—a shot routinely administered to people of all ages, including during pregnancy and as a standard series starting in infancy—declines quickly, from 70 percent efficacy in the first year after vaccination to less than 10 percent after four years. And while vaccinated individuals rarely show symptoms, they can still transmit the bacteria to others.

Pertussis can be severe in infants, especially those who are too young to be immunized. But current CDC numbers indicate that roughly 40 percent of expectant mothers do not get vaccinated against it. When that happens, or when a parent declines to vaccinate their infant with the three recommended doses, that infant is immediately at risk. In 2024, six infants in the U.S. died of whooping cough, and that number is poised to rise rapidly if more parents opt against vaccination, or vaccine mandates are weakened, as the bacteria spreads.

INFLUENZA

It often gets passed over because of its common seasonal influx, but influenza still causes some 6,300 to 52,000 deaths each year in the U.S. And this infectious agent is just a season away from spiking to record levels if vaccination rates decline further.

Last year's hospitalization rate during flu season was the highest it has been in 15 years, and vaccination rates for flu have been steadily declining year after year. That trend will likely be exacerbated by Kennedy's order delivered earlier this year to the CDC to halt a popular publicity campaign encouraging people to get the seasonal flu vaccine. "Flu is definitely something that can quickly come back and be more severe," says Kathryn Edwards. Flu vaccination is recommended each year for everyone over 6 months of age.

RUBELLA, HIB, AND MENINGOCOCCAL DISEASE

After the speedy reemergence of measles, pertussis, and flu, experts forecast the slower rise of three more vaccine-preventable diseases: meningococcal disease, a bacterial infection that leads to outbreaks of meningitis and can be deadly within hours of symptom onset; Hib disease, the bacterial infection known to spread in daycare centers, and which was once the most common cause of meningitis; and rubella, a viral illness that can cause serious defects or death in developing fetuses. In the Stanford modeling study, if childhood vaccination rates drop an additional 20 percent, rubella rates begin to climb. "That's really a scary future that we hope does not come to pass," says Lo.

PNEUMOCOCCAL DISEASE, MUMPS, CHICKENPOX, AND HEPATITIS

One of the harder-to-spot outbreaks will be pneumococcal disease, says Amy Edwards, as there are more than 100 strains of the causative bacteria. And pneumococcal vaccines—which are recommended for children under 5, adults over 50, and others with certain risk

factors—protect against only the 15 to 20 most deadly strains. Because there are already occasional outbreaks in the U.S. from strains not covered by the vaccines, Edwards notes, public health officials might not immediately notice if one of the more invasive, deadly strains, typically prevented by vaccination, begins to take hold.

Pneumococcal bacteria spreads through direct contact with saliva or mucus, and serious infection can lead to pneumonia, meningitis, or bloodstream infections. In 2024, 14 inmates at a correctional facility in North Carolina became ill with suspected pneumococcal disease. A CDC investigation identified the cause as serotype 4, a serious strain that causes high percentages of pneumococcal disease. That strain was not one of the strains included in the most recently recommended vaccine, PCV21.

As if this list weren't already long enough, next will come mumps and chickenpox, which have rare complications, including brain inflammation and severe skin infections, respectively, and hepatitis B, which used to be one of the most common causes of liver failure and sometimes required liver transplants in babies.

We've reached a pivotal point in this cascade of returned diseases. If Americans are able to improve vaccination rates over the next five years, that will be the worst of it. But if vaccination rates continue to drop, "we start to get into some of the scarier ones," says Amy Edwards. Namely, the resurgence of polio and diphtheria.

POLIO

Kathryn Edwards remembers being in elementary school when a friend became seriously ill with polio, and Edwards walked around her neighborhood collecting dimes in the original "March of Dimes" to fund the development of a polio vaccine at the behest of President Franklin D. Roosevelt. It was the era of "polio summers," when towns closed movie theaters, public swimming pools, schools, and churches to prevent transmission of the virus, which

An influx of patients with vaccine-preventable diseases will strain already struggling hospitals and medical centers.

affects nerves in the spinal cord or brain stem, leading to paralysis, trouble breathing, and sometimes death.

Largely thanks to an oral version of the vaccine, the U.S. eliminated polio in 1979. Since routine immunization against polio was introduced worldwide in the 1970s, the global incidence of cases of the disease has decreased by 99 percent. But predicting what might happen in the U. S. if polio vaccination rates were to dramatically decline is shrouded in some uncertainty, due to a change in the type of vaccine administered.

Until 2000, children in the U.S. were vaccinated with an oral polio vaccine (OPV), made from live polio virus in a weakened form. That vaccine protects the immunized person and, because that person sheds weakened virus, helps expose and immunize those around them as well.

On rare occasions (about 1 in every 2.4 million doses of OPV), the weakened virus reverts to a “strong” virus and can cause a case of the disease, occasionally leading to paralysis. Therefore, since 2000, in an effort to eradicate polio-virus globally, the U.S. switched to using an inactivated polio vaccine (IPV), which cannot revert to cause the disease. That means every

immunized person born in the past 25 years has received the IPV vaccine, which does not offer the benefit of secondary protection. Because of this, we don’t fully understand what percentage of a community needs to be vaccinated to prevent the spread of polio, says Roland Sutter, who served as chief of the Polio Eradication Branch of the CDC from 1997 until 2001 and then as a coordinator of the Global Polio Eradication Initiative with the World Health Organization. If polio vaccination rates were to considerably decrease, “it’s quite unpredictable what is going to happen,” he adds. “This is uncharted, new territory for polio.”

DIPHTHERIA

In the 1920s, diphtheria was one of the most common causes of illness and death among children in the U.S. This serious bacterial infection creates a gray, leather-like coating in the mucus membranes lining the throat and nose, obstructing breathing. “It is terrifying to watch a child not be able to breathe,” says Amy Edwards, who has treated children with diphtheria in sub-Saharan Africa. “Even if with modern technologies we can save them, it is horrible to watch a kid be in the ICU for a week.”

“We are a stone’s throw or a plane ride away from whatever infectious disease emerges next.”

Thanks to widespread uptake of the diphtheria vaccine, the last U.S. confirmed case of respiratory diphtheria was reported in 1997, though the bacteria that cause the disease still circulate in other countries. According to the Stanford modeling study, if vaccination coverage drops 35 percent below current levels, diphtheria will begin a slow but steady return.

REVERSING COURSE

While it is now often—but not always—possible to save children sick with diphtheria or many of the other vaccine-preventable illnesses, they often require intensive healthcare interventions. For instance, babies under 6 months old with whooping cough need prolonged pediatric ICU stays, often hooked up to a ventilator or even a heart-lung bypass machine. Because of this, an influx of patients with vaccine-preventable diseases will strain hospitals and medical centers already struggling with staffing and funding shortages since the pandemic. And these life-saving procedures are not without risks and potential long-term health effects.

Additionally, new restrictions on Medicaid payments included in President Donald

Trump’s sweeping budget bill signed into law this summer, will likely lead to significantly less revenue for hospitals, which will in turn have fewer staff and resources to care for patients. “If we start taxing a healthcare system that is already broken with sicker and sicker kids, you’re putting pressure on a system that’s already crumbling,” adds Amy Edwards.

Another overarching concern is the spread of vaccine-preventable illness around the rest of the world. In June, when Kennedy withdrew a \$1.2 billion funding pledge from GAVI, a leading international vaccine organization, global health leaders were stunned and worried. The U.S. cannot keep itself safe from infectious diseases in isolation, says Sutter. If international health systems are less equipped to prevent infectious diseases, those diseases will spread, mutate, and arrive on U.S. shores. “This is one world,” says Sutter. “We are a stone’s throw or a plane ride away from whatever infectious disease emerges next.”

Facing the potential return of these once-prevalent diseases, it feels at once bewildering and reassuring to know we already have the tools to prevent them. “Vaccinations are the

greatest testimony to scientific advancements in medicine, particularly pediatric medicine, that we've ever seen," notes Kathryn Edwards. "We have got to work very hard to make sure some of these things that could happen, don't happen."

Parents want to keep their children safe and healthy, and most parents trust their primary care physicians, so experts recommend that pediatricians and other healthcare providers always ask if children are fully vaccinated. And parents should feel encouraged to discuss the relative risks and benefits of vaccines and infectious diseases with their doctors, says Pastula. "Any healthcare provider would be happy to walk through that," he says.

The good news is that even a small boost in vaccination rates could make a big difference. For example, a modest 5 percent increase in vaccination rates over 25 years would reliably prevent measles from returning to endemic levels, says Lo. "A pretty small fraction of the population could make a big difference for the United States."

Preventing a new wave of old diseases will require the government and public to support and raise vaccination rates to high coverage, yet all signs suggest that U.S. health agencies and public sentiment continue to head in the opposite direction. "I worry about it greatly," says Kathryn Edwards. "We need to share the clear message that the benefits [of vaccines] are really much greater than the risks."

Because, at the very least, we can all agree on one thing, adds Amy Edwards: "Kids shouldn't die. Any child dying is one too many." ☺

MEGAN SCUDELLARI is a science writer based in Boston, specializing in the life sciences. Her work has been featured in the *Boston Globe*, *Nature*, *Newsweek*, and others. She is also co-author of a college biology textbook, *Biology Now*.

The Highest Pressure Job on Earth

In the darkness of the deep sea, “saturation divers” tread the razor’s edge of what a human body can endure

BY CHARLES DIGGES

CHRIS LEMONS, A SATURATION DIVER from England, is in the rare position of having witnessed his own death. All roughly 40 minutes of it were recorded on video, which he watched the next day aboard the *Bibby Topaz*, the 350-foot vessel he was diving from—rooting for himself to pull through.

In the smudgy black-and-white footage, Lemons is seen lying on his side at the bottom of the North Sea atop something called a drilling template—a jungle gym of pipes that subsea oil drillers use to manage multiple wellheads—his diving suit and helmet making him resemble a toppled astronaut. For the first several moments, his limbs twitch unnaturally, his hands piteously reaching through the dark toward the remotely operated submersible that his ship sent down to find him.

Then the twitching stops, the blackness of the surrounding sea framing his lonely demise. He is 300 feet below the surface of the North Sea and he can’t breathe. In a freak technical failure, the *Bibby Topaz* had begun to drift downstream away from him at the exact moment his air hose became entangled in the template. The hose runs to his diving bell, and his diving bell is connected by cables to the ship—and for one tense moment, Lemons himself is the only thing holding the errant 8,000-ton vessel in place.





HATS OFF Kirby Morgan dive helmets (known as “hats” in the profession) are the sat diver’s most crucial piece of equipment, the lifeline delivering the proper mixture of gases as they work at great depths. This one belongs to Jerry Shepherd and is missing the removable helium reclaimer essential to using it on saturation dives.

Then the hose snaps.

“It was like a jack being pulled from a speaker,” Lemons told me when we spoke recently. “I lost all communication, which puts you in a very lonely place. Then the hose, which provides an infinite amount of gas—suddenly I had nothing to breathe at all.”

It would be a half an hour before the navigation glitch was solved and the ship was able to reposition the diving bell to rescue Lemons. When his unconscious body was eventually recovered and he was miraculously revived by his diving partners, Dave Yuasa and Duncan Allcock, Lemons had gone all that time without breathing.

For most of us, observing our own passing, especially amid such a forlorn and desolate backdrop, might make for rather difficult viewing.

Not for Lemons.

“I think I’m sort of like everyone else who’s watched the video, thinking—does he make it?” he said.

He made it. Others didn’t. Traumatized by the accident, which was streamed to monitors aboard the *Bibby Topaz* as the emergency unfolded, some of Lemon’s crewmates quit working with divers altogether, he said. But for him and his dive mates, the events of that 2012 accident, 115 miles off the coast of Aberdeen, Scotland, produced the opposite effect.

“It has been a positive in our lives, in a strange way,” he said. “It gave us more confidence.”

Breathing a mixture too rich in oxygen gives you something akin to an acid trip with a side of convulsions.

Three weeks later, Lemons and his dive partners were back at the bottom of the sea to finish the job cut short by the near tragedy.

If you're not a saturation diver, it's hard to imagine these terrifying events as a good day at the office—but it was. While at work, Lemons and his colleagues spend their days anywhere from 300 to 1,000 feet below the surface and remain at pressures up to 30 times that of sea level for as long as a month. To do so, they live in pressurized chambers aboard ships or oil rigs, from which they descend in diving bells to their job sites at the bottom of the sea—as dark, remote, and inhospitable a climate as can be found on Earth. In such a place, close scrapes like Lemons' are almost routine.

“When people hear the word ‘diving,’ they often think of guys in fins swanning about gracefully in clear blue water,” he said. “This job isn’t that. On 9 out of 10 dives, visibility is near zero. Seeing what you’re doing is a luxury.”

Perfect by the United States Naval Submarine Medical Research Laboratory in the late 1950s, saturation diving—called “sat” by those in the business—quickly became a boon to the oil industry and led to a massive proliferation of offshore oil production platforms. In the Gulf of Mexico alone, their numbers mushroomed from only a few hundred to nearly 3,000

by 1972, thanks largely to sat divers who could live at depth pressure to build the undersea infrastructure that offshore drilling required. The number has been climbing ever since.

“Essentially, we’re the glorified plumbers for this system,” Lemons said with sardonic understatement.

But plumbing at these depths isn’t just a matter of turning wrenches and laying pipe—it’s a fight with the limits of physics and biology. Saturation diving treads the razor’s edge of what a human body can endure.

Every trip to the seafloor is a negotiation with gas laws and physiology that cut divers little slack. Without the sealed, pressurized chambers they live in aboard ships for weeks at a time, the special gas mixtures that they breathe, and the diving bells that ferry them from the chambers to the ocean floor, their bodies would seize, suffocate, or come apart from within. Those who do this work survive only because we have managed to forge a fragile scientific truce with the laws governing gases under intense pressure at depths humans were never meant to plumb.

THE HUMAN FRAILTY that saturation diving eludes is the tendency of our bodies to absorb gases when we’re under high pressures and trying to breathe. Deep underwater, inhaling regular compressed air pushes

The helium also makes the divers talk like a chorus of chipmunks for the duration of their saturation.

inert gases—chiefly nitrogen—deep into blood and tissue. The air we breathe as we walk down the street is about 78 percent nitrogen and 21 percent oxygen (with argon and other trace gasses making up the rest). On a day-to-day basis, our bodies essentially ignore it. It's inert.

But once we dive to about 30 feet underwater, the pressure on us doubles from that at sea level, making the gases behave differently. On a typical scuba dive, when a diver breathes regular air, nitrogen slips into blood and tissue, building a load that can explode into bubbles on the way back up. Ascend back to the surface too quickly and your body essentially becomes a shaken can of beer. Nitrogen fizzes out of solution with your blood and tissues, blocking circulation, lodging in joints, even provoking stroke-like symptoms if they shut off oxygen to the brain. Divers call this decompression sickness "the bends." Bad cases can, and sometimes do, result in death.

Things only get worse the deeper you go. Nitrogen becomes a timebomb in your tissues and makes you drunk to boot—a state known as nitrogen narcosis. But breathing a mixture too rich in oxygen gives you something akin to an acid trip with a side of convulsions. It is only when divers are fully saturated with inert gas—in sat, that is—that they're safe from the nasty side effects that breathing produces below about 300 feet, where the pressure is 10 times that experienced by a body at sea level.

Before the advent of saturation diving, humans could work only about a half hour at no greater than about 120 feet below sea level before having to ascend. The longer divers stay down, the more nitrogen accumulates in their system, so even after this short stay at depth, they had to make numerous lengthy stops as they rose to let the gas slowly dissipate. That made getting any work done underwater a pain. Think of sending a carpenter to the 40th floor of a skyscraper

to hammer one nail, then lowering him in an elevator that doesn't descend until the next morning.

Saturation functions by delaying the decompression process. Sat divers enter what's called a saturation complex, which sits aboard a dive support vessel or oil rig. They are tightly sealed within it and brought to the pressure at the depth where they will work and remain there—unable to leave for *any* reason—until the job is done. Missing birthdays, weddings, anniversaries, and funerals is part of the work. It is here, topside, that they will live for weeks at a time, descending in diving bells to the job site for their shifts. Their isolation ends only when they are depressurized—a days-long process that comes when their work is finished.

THE FOLKS WHO DO this kind of work are almost entirely men (there are four women known to have worked as sat divers) between about 25 and 40 years old. Any younger and they wouldn't have accrued the experience needed to join the ranks. Much older and they might not withstand the rigors of the job as well.

Anecdotally, there are only about 7,000 to 12,000 of them in the whole world, possibly fewer, notes Jerry Shepherd, head instructor at the South Louisiana Community College dive school. Only 1 in 15 of his students ascends the professional ziggurat to saturation. Fewer still will stick with the job for an appreciable length of time—the first month-long dive often flushing out the fainter of heart. For those who do stay, said Lemons, it's imperative that they be drawn to—rather than repelled by—the job's idiosyncrasies and risks.

For one, there's really no fixed schedule once you graduate and land a spot on a dive contractor's roster. Much of the job is waiting by the phone.

In early June, when I had lunch in New Orleans with two Gulf of Mexico sat divers named Jeff and Dave, who

preferred to withhold their last names for professional reasons, both men were looking forward to a few weeks off. By the time they ordered their second beer, though, their phones had rung with assignments for a saturation tour starting the next morning. That's how quickly things can change. At the same time, a successful diver will work around 160 days a year, cumulatively, and all that downtime, said Shepherd, can lead some divers to act up while shoreside, giving the profession a ram-bunctious reputation. Bar fights, relationship problems, and run-ins with the law are frequent extracurriculars, according to many familiar with the profession. But all that stays onshore: The claustrophobic environment of the living chamber also makes the job more suitable for people who can be even-tempered and agreeable while they're on the clock.

"Assholes have a way of not lasting too long in sat," Jeff told me.

Those graduating from Shepherd's class will have years of shallower dives ahead of them before they will even be considered for sat. They'll first do regular compressed air scuba dives to about 120 feet, then graduate to breathing mixed gasses on deeper jobs with higher pay. From there, explain Lemons and Shepherd, with a bit of luck, your dive supervisor might single you out for a promotion to saturation. It pays to stick it out. Sat divers routinely bring home \$180,000 to \$200,000 a year.

"If you can make it to sat, that's good money for sitting in a steel chamber for half the year," said Shepherd.

A STANDARD SATURATION CHAMBER resembles a giant hamster tube made of metal cylinders. Depending on the size of the dive support vessel, it accommodates anywhere from six to 24 divers. Each complex has living quarters that are slightly less spacious than an airport hotel shuttle van, its walls lined with bunks abutted by a small sitting area and table. It's almost exactly like being locked in a space capsule.

Once in the complex, divers are pressurized—or "blown down"—over the course of several hours to the pressure they'll be working in once they descend to depth. At the same time, the air inside the saturation chamber phases over to a mixture of helium and oxygen, called heliox. Under pressure, the ordinary air we breathe at the surface becomes toxic. This removes



MIXOLOGIST Jerry Shepherd, head instructor at the South Louisiana Community College dive school, shows off a diving manifold, a system of valves that mixes the gases a sat diver would breathe during a dive.



HIGH PRESSURE PROFESSION

Author Charles Digges chats with Jerry Shepherd among decompression chambers used to teach students about working at tremendous pressures. The chambers can also be used treat divers suffering from decompression sickness.

nitrogen, which, under pressure, also affects neurotransmitter functions in the brain, essentially making it an anesthetic. Oxygen levels, too, must be managed—at pressure, too much of the gas turns poisonous, triggering spasms, hallucinations, and chest pains. Heliox therefore contains no nitrogen at all and only a tiny percentage of oxygen to keep the divers alive—at pressure, even a small dose is enough. The lighter helium, meanwhile, is very easy to breathe. Any heavier gas at saturation depth would make inhaling like trying to suck thick soup through a straw.

The helium also makes the divers talk like a chorus of chipmunks for the duration of their saturation. The communications lines in most saturation units come equipped with special descramblers that aim to make the high registers of the diver's helium voices more intelligible to the staff monitoring them from outside the complex. But their use is limited.

"All they really do is add bass to the high-pitched treble of the helium voices, turning Donald Duck into Oscar the Grouch," Shepherd told me.

Once fully pressurized to the depth where they'll be working, it's time for the downward commutes to start. A smaller crew of divers climb into the diving bell, an egg-shaped steel orb that detaches from the living quarters and is kept at the same pressure. The bell, which is about as

“During decompression, you understand you’re not so much being paid to dive as you are to simply wait inside a can.”

spacious as a bathroom stall, is lowered on cables from the ship to the seafloor, its two-inch-thick steel walls protecting the divers from the pressure. Lemons calls it the “taxi to the job site,” though his description of its creaky, shimmying, and ever-darkening descent to the depths that can last up to an hour made me think of an elevator ride into the abyss. Crowded into the bell with the divers are their bulky Kirby Morgan dive helmets—which the divers call “hats.” Typically, divers work in groups of three for six-hour shifts, four teams rotating so work goes on around the clock.

Coiled on hangers in the bell are the braids of their umbilical hoses. These are exactly what they sound like, delivering, as they do, the heliox, electricity, and fiber-optic lines for communication. Each hat is equipped with a microphone and a camera which keeps the divers in touch with their supervisors on the dive support vessel. Given the frigid depths at which the divers operate, another tube running through the umbilical carries warm water to channels in their neoprene drysuits.

When the ride to the seafloor ends, divers exit the bell through the hatch. Since the pressure of the bell equals the pressure at the working depth, the seawater is kept at bay. Two of the divers then put on their helmets with the assistance of the third, referred to as the bellman, who remains in the bell to manage the umbilicals as they snake out behind the divers. Each diver has about 150 feet of slack to wander.

It’s at this point, once you’re finally in the water, that the pressure of the job—both literal and metaphorical—can catch up with you, Dave, the Gulf diver, tells me.

“A couple hundred feet above you is a ship with 160 people on it—cooks, dive support techs, navigators, swabbies—and they’re all there so you can tighten this one bolt at the bottom of the ocean,” he said. “You don’t want to fuck it up.”

After their shifts end, the divers ascend in the bell to the pressurized living chamber aboard the ship. The bell is mated to the chamber to maintain equal pressure between the two. The divers then step through an airlock back into their heliox-filled metal cocoon, still sequestered from an outside world that’s only inches away.

When I visited Shepherd at his dive school in Morgan City, Louisiana, he showed me an array of decompression tables spelling out the wait times for various depths dived.

In general, the standard is one day of waiting for every 100 feet of depth, plus an extra day, meaning a sat team that has been working 1,000 feet down—the maximum beyond which sat divers don’t go to avoid high-pressure nervous syndrome, characterized by tremors and neurological damage—must wait 11 days before they can emerge into sea level air. As decompression proceeds, the pressure is gradually reduced, with several stops along the way to avoid shock. The gas mixtures are also changed as the divers “ascend.” Helium is

“It is amazing what you normalize.”

gradually washed out, oxygen levels are tuned to remain safe, and the divers are eased back toward surface air, Shepherd explained.

These are the longest hours of the job. “During decompression, you understand that you’re not so much being paid to dive as you are to simply wait inside a can,” Lemons told me.

Divers typically devote these long hours to books, movies, and catching up with home via whatever internet connection is available. While some dread the tedium, Paul Dinesson, a Norwegian saturation diver I interviewed, put it to good use producing notes for what would later become a three volume, 2,000-page autobiography, as yet unpublished, of his life at the bottom of the North Sea—giving new meaning to writing under pressure.

WHILE THE DIVERS ARE at depth, their topside support vessel is held in place by a dynamic positioning system—a GPS-guided network of thrusters that acts as an electronic anchor parking the ship in one spot regardless of where the sea and wind want to pitch it. These systems have so many redundancies that their failure is almost unthinkable.

Yet this was precisely the nightmare that unfolded on the night of Lemons’ fateful dive. As the dynamic positioning system of the *Bibby Topaz* glitched out, the ship drifted with the North Sea current, dragging the diving bell, Lemons, and his dive partners through the water column like marionettes before Lemons’

umbilical snagged on the drilling template they were inspecting that day.

“I didn’t see any bright, beckoning lights when I was out,” Lemons told me. “When I came to in the bell, I was confused, though I understood from the expressions on Dave [Yuasa] and Duncan’s [Allcock’s] faces that something serious had happened. But it would be a while before I connected it to myself.”

A paper published on the factors that saved Lemons highlighted the thorough rescue training of the dive staff, the spot-on mixture of his diving gas, which allowed his tissues to hoard oxygen, and the fact that he did, indeed, lose consciousness, which lowered the demands of his system. But the alignment of all those elements is an awful lot to depend on if something goes wrong during a sat dive.

The most dramatic accidents in saturation diving history tend to do with the pressure differentials between the living chambers and the sea level environment of the vessels where they sit. While Lemons’ experience spurred several industry-wide safety upgrades in backup breathing sources and more navigational redundancies, accidents do happen.

The most dramatic of them tend to highlight the collision between our bodies—which are so finely tuned to living at around sea level—and the iron laws of physics governing the gases we breathe when they are subjected to 30 atmospheres of pressure.

Just how powerful those collisions can be was viscerally illustrated in 1970, when a Gulf diver named

Donald Boone had a very unfortunate experience on the toilet in his living chamber. In these early days of saturation diving, the toilets operated like simple airlocks. An inner valve on the toilet would be opened to drop the waste, then be closed. An outside tender would then open an exterior valve to suck the contents into a holding tank at sea-level pressure. In Boone's case, both valves were mistakenly opened at the same time while he was still seated on the toilet. As a result, his small and large intestines were sucked to the outside of his body as the highly pressurized air inside the chamber rushed outward.

Boone survived, but it took some complex logistics. Two trauma surgeons were flown by helicopter to his dive vessel, then brought down to Boone's pressure in a hyperbaric chamber. In a ghastly procedure, using only local anesthetic because the pressure inside the chamber made standard gaseous anesthetics impossible to use, they operated on Boone inside the sat complex, stabilizing him enough to endure the days-long decompression and another more comprehensive surgery on shore. Extra valves have since been added to sat chamber toilets to prevent this particular horror from repeating itself.

A more lethal tragedy that haunts sat divers is a 1983 accident aboard a Norwegian North Sea drilling rig called the *Byford Dolphin*, where a routine transfer of divers from the diving bell to the living chambers went gruesomely awry. A clamp that secured the bell to the living chamber opened prematurely, instantly exposing the divers inside to explosive decompression. In the blink of an eye, the chamber went from depth pressure to sea level pressure like a shaken soda can. The pressure differential was so great that one diver was literally torn apart where he stood. Three others inside the chamber died immediately as nitrogen bubbles in their blood and tissue burst. A fifth man, a tender outside the chamber, was struck and killed by the bell as it was flung like a cannon ball away from the chamber.

Less dramatic, though still terrifying stories are a part of every diver's personal history. Jeff told me of having a several-ton load nearly dropped on him as it descended from his dive vessel. Shepherd spoke of his fear of manta rays, who lie camouflaged on the sea floor, and who, when spooked, dart to the surface. When this happens, a diver's umbilical can get scooped up by the

forked, fleshy appendages around the ray's mouth, and drag the diver to unexpected and possibly fatal decompression. Norway's Dinesson was nearly sucked under a piling to an oil platform as it was being repositioned. So long as they keep diving, their harrowing stories pile up.

So why would anyone keep going in this line of work, I asked Lemons.

"I think the bottom line is that it is amazing what you normalize," he said.

For the past few years, Lemons, now 45, has been working topside as a dive supervisor, but not for any reasons connected to his brush with death. In fact, he went on to dive in saturation for 10 more years. His experience was made into a documentary called *Last Breath*, itself subsequently developed into a film by the same name. In connection with that, Lemons is currently on a sabbatical from the diving world to do public speaking, but plans to return.

His persistence in the industry, he suggested, might have something to do with his new relationship to his own mortality. As Lemons sat at the bottom of the North Sea after the bell and his dive partner had been dragged hopelessly away by the current towing the *Bibby Topaz*, panic was replaced by something wholly different.

"I can still feel how the fear drained out of me," he told me. "I'd done all I could, and rather calmly thought, well, this is it—if this is how I have to go when my time comes, it really wasn't so bad." ☺

CHARLES DIGGES is an environmental journalist who edits the website of the Norwegian environmental group Bellona.

The Cure Hiding in a Rotten Eggplant

Bacteriophage therapy's new renaissance

BY LINA ZELDOVICH



A

YOUNG BOY IN NEBRASKA may well have been saved thanks to a particular piece of rotten egg-plant collected in South Africa. And a virus it contained.

Like many other kids, Hudson Campbell was no stranger to ear infections. But his were incredibly persistent. Antibiotics usually seemed to help initially, but once the course was over, the infections would come roaring back. Born in 2017, by age 2, he had already gotten ear tubes surgically implanted to drain the excess fluid the infections produced. A second set of tubes inserted in 2020 fell out within weeks—his infected ears had too much fluid in them.

That fall, doctors took a sample of bacteria growing in Hudson's ears. The result was troubling: The bacteria were *Mycobacterium abscessus*. Frequently resistant to antibiotics, not many known drugs can fight the pathogen. The infection threatened his hearing, but also, if it spread, could quickly make its way beyond his ears.

Hudson's bacterium is, of course, far from the only drug-resistant infection spreading. Its relative, *Mycobacterium tuberculosis*, which causes TB, has become notoriously resistant to antibiotics. Others include strains of *Salmonella* and Staph. Each year, some 2.8 million Americans struggle with antibiotic resistant infections and more than 35,000 people die from them.

Yet, many of these infections do have cures. Known as bacteriophages, bacteria-slaying viruses just don't yet exist on the shelves of hospital pharmacies. Instead, they lurk in strange places, like sewage, soil, and decaying vegetables.

BY SUMMER 2021, just six months after doctors identified *M. abscessus* in his middle ears, Hudson's hearing started to disappear. One morning he had woken up and said, "Mom, I can't hear you." His mother, Kylie Campbell thought he was just being a mischievous 3-year-old. But three days later, the family was coming back from

vacation, and Hudson was sitting in the back seat with his two younger sisters. He kept complaining that he couldn't hear the video playing in the car. "I turned it up almost as loud as it could go, and he could barely hear the TV," Kylie Campbell recalls. Sitting in the car with the sound blaring, she realized he meant it. That week Hudson had lost much of his hearing.

Doctors weren't sure if Hudson's infection or the antibiotics used to treat it caused his hearing loss. Late in 2020, Hudson had been outfitted with a so-called PICC line—a peripherally inserted central catheter—a long, thin, flexible tube that went into his upper arm and threaded into a large vein near his heart, so he could receive an antibiotic called amikacin, which can only be given intravenously. But in addition to wrecking his gut microbiota—causing such bad gastrointestinal side effects he could barely leave the house to participate in normal little kid life—amikacin can also cause hearing loss.

Whether it was the drugs, the infection, or a combination, Hudson's eardrums became so damaged they could no longer transmit sound to the auditory nerve, which passes it to the brain. Hudson became profoundly deaf in his left ear and severely deaf in his right. His hearing could be restored with cochlear implants—electronic devices that bypass the damaged parts of the ear and "talk" to the auditory nerve directly—but whether they would work properly amid a raging *M. abscessus* infection was the question. Doctors were also worried that if amikacin stopped working, Hudson's infection would spread.

The bacteria did spread, next infecting Hudson's mastoid bone, a part of the skull located behind the ear. His parents took him to the Mayo Clinic for

Bacteriophages have their own evolutionary incentive to keep up with and outsmart their prey.

mastoidectomy, surgery that cleaned the dead cells from the bone with the hope of clearing the infection, too. He seemed to improve. In 2022, his medical team decided he was ready for a cochlear implant in his left ear, where he had lost almost all hearing. Time was of the essence because without regular stimuli, the auditory nerve could quickly atrophy. The surgery went well, but the implant didn't last—the infection returned with a vengeance. “About six to eight weeks later, the implant fell out of his ear because the infection was so bad,” Kylie says.

On Good Friday of 2022, Mayo Clinic surgeons took the implant out of Hudson's left ear and implanted another into his right. The new implant took well, but Hudson's left ear was not getting better.

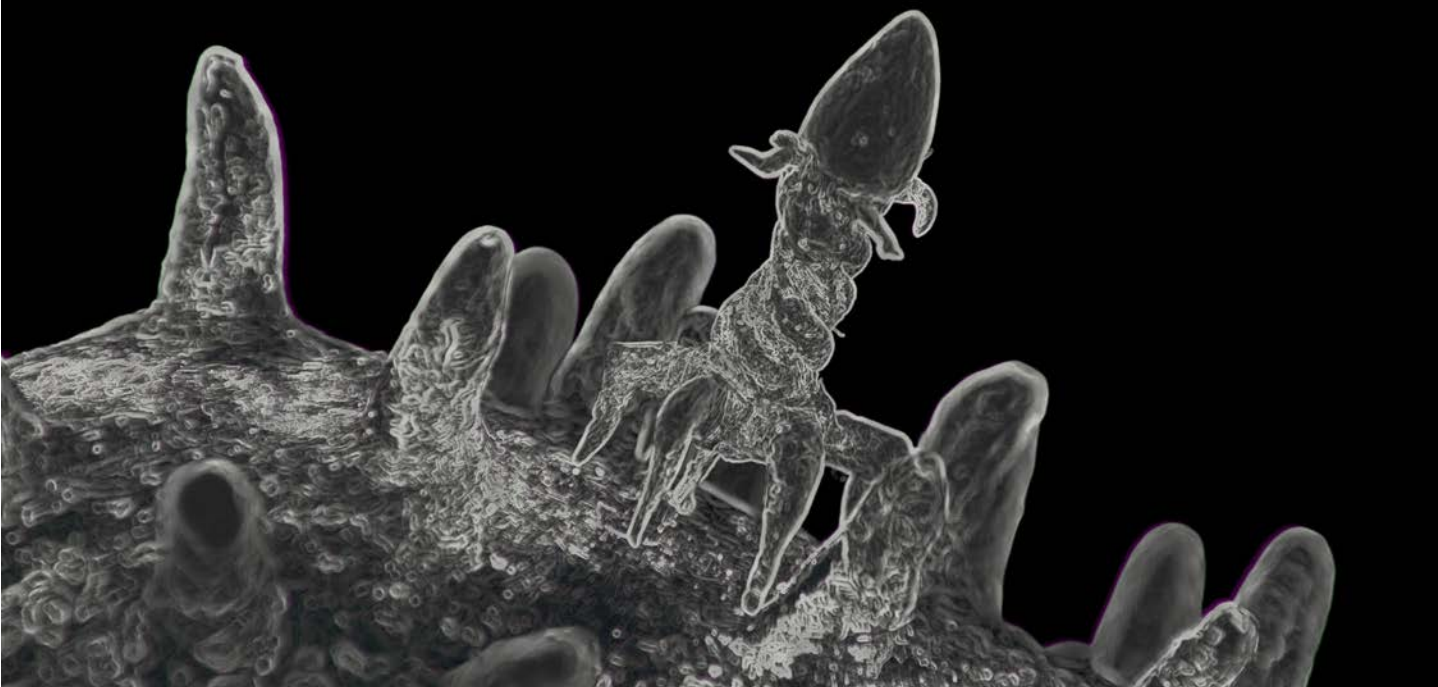
Back in Nebraska, a pediatrician who had treated Hudson at the Children's Nebraska hospital in Omaha named Bradford Becken had a bold idea: Enlist a virus to fight off the aggressive bacteria.

EVOLUTION HAS TYPICALLY BEEN our enemy in the world of antibiotics. These drugs exert their lab-crafted killing pressure on bacteria, prompting the microbes to evolve new ways to defend against or disarm the medications. Some bacteria can eject antibiotics from their cells before they can act, others produce enzymes that cut antibiotic molecules to shreds. And with survival of the fittest as the law of the microscopic land, the more antibiotics we use, the more selective pressures they exert, the tougher the survivors—and the less effective our antibiotics.

Evolution, however, could be our collaborator in a different, dynamic class of treatments. Bacteriophages, the viruses that attack bacteria only and are harmless to humans, have their own evolutionary incentive to keep up with and outsmart their prey. Unlike broad-spectrum antibiotics, which typically target whole classes of bacteria in our bodies—the bad and the good, hence their negative side effects, such as diarrhea and yeast infections—phages are very targeted, preying on very specific bacteria. This is excellent news for our bodies and our commensal microorganisms.

But it can also make finding the right phages tricky. Even within one strain of *M. abscessus*, there can be big enough variations so that not every *M. abscessus*-targeting phage may work efficiently enough to kill off the bacterium, explains Graham Hatfull, a professor of biotechnology at the University of Pittsburgh whose research focuses on mycobacteria species. Hatfull also runs SEA-PHAGES, a research course for which students search through soil, compost, and other substances to identify and catalog novel bacteria killers in different parts of the planet.

And that's where the expired eggplant comes in. Some years ago, a SEA-PHAGES student in South Africa was digging through a pile of garbage, from which they fished out a half-rotten eggplant chunk. Living on the chunk was a phage that was fairly adept at attacking *M. abscessus*. The student noted the phage activity against *M. abscessus*, named the phage Muddy, and added it to the collection, which today totals about 28,000 strains of bacteria-killers.



BACTERIA-EATERS Bacteriophages, whose name was inspired by the Greek word *phagein* (“to devour”) are viruses that have evolved to prey on bacteria. In 1919, French microbiologist Felix d’Hérelle isolated one strain of these targeted viruses and used it to treat three children dying from dysentery. All three were cured.

Becken had heard about phage therapy, but never used it before, so he reached out to Hatfull to ask if there might be a phage in his collection to try against Hudson’s *M. abscessus*. It wasn’t the first such email Hatfull had received. He had created a few phage treatments before for similarly stubborn cases. If Hatfull’s lab found the right phage, Hudson would become the first young child in the United States—that his medical team was aware of—to be treated with phage therapy.

He wouldn’t be the first in medical history, though. In fact, the first documented pediatric use of phage therapy was more than a century ago. The children, three brothers aged 3, 7, and 12, were treated in a children’s hospital in Paris in 1919. The boys were dying from dysentery, caused by a *Shigella* bacterium, which had already killed their sister. Antibiotics hadn’t yet been discovered and wouldn’t become widely available for another three decades. But French microbiologist Felix d’Hérelle had just zeroed in on something that killed the dysentery bug, which he correctly identified as a virus that preys on bacteria.

That insight struck when one of d’Hérelle’s dysentery patients managed to beat the illness seemingly on his own. As he got better, d’Hérelle noticed that *Shigella* began to disappear from the patient’s stool samples. D’Hérelle seeded the stool samples onto petri dishes with plenty of beef bouillon to help feed the deadly bacterium, but *Shigella* dwindled there also, leaving behind clear patches where it originally had been. Something was killing off the bacteria. So d’Hérelle devised a clever trick to isolate the mysterious agent.

He passed the remaining bouillon through a Pasteur-Chamberland filter with holes so small that fluids could trickle through, but bacteria couldn’t. He ended up with a clear liquid, seemingly lacking all microbial life. But when he added *Shigella* back into the liquid, the bacteria were gone by the next day. “They dissolved like sugar in water,” d’Hérelle later wrote. “What caused my clear spots was in fact an invisible microbe.”

He named the curative agent “bacteriophage,” from the Greek word *phagein*, which means to devour or eat.

As antibiotic resistance grew, it became clear that alternatives were needed.

D'Hérelle and his colleagues tested phages on themselves first, found no adverse effects, and then gave the medicine to the children, all of whom recovered within days. Later, d'Herelle used phages to treat a variety of infections, including the plague, caused by the bacterium *Yersinia pestis*, which had no cure.

In the 1920s and 1930s, medics in Europe, North America, and the Soviet Union successfully used phages to treat a range of infectious diseases, including dysentery, cholera, and staph. However, in the U.S., phages eventually fell out of favor, partially because of the advent of more broad-spectrum antibiotics and partially because phages had to match the exact subtype of bacteria the person was infected with to be effective. So with effective antibiotics on hand by the mid 20th century, many U.S. physicians grew less inclined to turn to phage therapy, some even expressing doubt as to their efficacy.

Still, in countries of Eastern Europe and the Soviet Union, phages were used alongside antibiotics, especially when the latter failed to work. In Georgia, which was then part of the Soviet Union, health officials created an entire research institution, today called George Eliava Institute of Bacteriophages, Microbiology, and Virology devoted to the production and study of bacteriophages. In the 1970s, Georgian researchers managed to cultivate a phage active against methicillin-resistant staphylococcus aureus, or MRSA, a dreaded superbug. When the Soviet Union fell apart, Georgian scientists began to arrive in the U.S., bringing their bacteriophage knowledge with them.

But decades of distaste for phage therapy, combined with the Cold War cast a pall on bacteriophages and other corners of Soviet biomedical research as “commie medicine,” made their uptake slower in the U.S. Yet, as antibiotic resistance grew, it became clear that alternatives were needed. In 2016, for the first time, the FDA greenlighted a phage treatment for an experimental case. It was granted for Thomas Patterson, currently a psychiatry professor at the University of California, San Diego, who was near death, infected by bacteria that appeared resistant to all known antibiotics. When phages vanquished his bacteria, saving his life, a paradigm shift ensued. Over the past several years, bacteria eaters have been climbing their way back in the U.S. from scientific obscurity. But slowly.

Part of the challenge is still finding the right match, which is typically done by pitting phages and bacteria against each other in the lab and looking for a winner. So Becken sent Hatfull a sample of Hudson's bacteria. At Hatfull's lab, workers tested a number of phages against the sample, but none were successful. A few weeks later, Becken sent another sample—with the same result. But Becken was tenacious and sent yet another one. Hudson's third sample found a match, a virus that had descended from the one collected from that mushy eggplant. It was Muddy's progeny.

When Becken learned that Hatfull's lab found the match, he was excited and nervous. “It was the first phage patient that I've ever had, and the first phage patient this hospital has ever had,” he reflects. “And I was very hopeful, because I didn't know what would

come after a phage if it didn't work. I wasn't sure what else was out there."

Becken filed an Investigational New Drug request with the FDA, and in May of 2023, Hatfull's lab prepared Hudson's phages.

HUDSON'S PHAGES ARRIVED at the Children's Nebraska hospital in little glass bottles, ready to be administered intravenously and directly into his left ear to give *M. abscessus* a double blow. Hudson would also remain on his antibiotics for an extra punch. Phages and antibiotics can work synergistically, each killing the respective susceptible bacterial population. "Hudson was admitted to the hospital because you can't send a phage to CVS," Becken says, adding that this also afforded extra protection in case he had any side effects during his first few phage applications.

He had none, so the rest of his treatments were done as outpatient visits, and the results were fast. "It was just amazing to watch," Kylie says. "Within the first month of starting it, his ear had completely dried up. We went to Mayo, and they said his ear was better than it had looked in years. You could just tell he was feeling better."

Hudson received phages for several months. "I probably treated Hudson with the phage longer than he needed to be treated," Becken says, but he was worried that *M. abscessus* may rebound once therapy ceased, and he wasn't taking any chances. Around September 2023, Becken deemed Hudson cured and stopped the phages. The bug did not return. A few months later, Hudson got the cochlear implant in his left ear, and it stayed for good.

Since Hudson, more patients at Children's Nebraska have received phage therapy and some are currently being evaluated for the treatment, Becken says. "Phages are fascinating, because I see issues with antibiotic resistance every day, and every time you use an antibiotic, you increase antibacterial resistance," Becken says.

Bacteria can develop resistance to phages, too, but phages will respond in kind, boosting their attack prowess. "Bacteria and phages have been racing against each other for millions of years," explains Sandro Sulakvelidze, a Georgian expat and researcher who founded Maryland-based phage company Intralytix in 1998. Sulakvelidze's company manufactures phage

spray used in the food industry to eliminate pathogens such as listeria, salmonella, and campylobacter. "All we need to do is to sic them on each and harvest the winner."

That's exactly what happened in Hudson's case, explains Hatfull. The original Muddy phage wasn't effective against Hudson's *M. abscessus* strain, but its progeny was. "We kind of played this battle between the bacteria and the phages," he says, which made the phage evolve to be a better killer.

This approach to battling bacterial infections will likely be increasingly important. Fighting antibiotic-resistant infections already costs upward of \$4.6 billion in healthcare costs in the U.S. annually. And the death toll is climbing. Experts warn that between now and 2050, antibiotic-resistant superbugs will claim 39 million lives around the world. The United Nations has an even grimmer prediction: 10 million deaths annually by 2050.

For Kylie and her husband Gregg, seeing Hudson living his life like most other children was a gift. Before the phage therapy, "Gregg and I were almost at the point of withdrawing all medications because it was hurting Hudson physically so bad, and we felt like we were never getting any better," she says. "And now he's enjoying hearing with both ears with 95 percent accuracy."

Today, Hudson, now 9, plays multiple sports, and one of his favorite activities is swimming. "From a mom's perspective, I would say that without phage therapy, we would have never cleared the infection," Kylie says. "It was a game changer." Thanks to a virus hidden away in a rotten eggplant. 🥚

LINA ZELDOVICH grew up in a family of Russian scientists, listening to bedtime stories about volcanoes, black holes, and intrepid explorers. She has written for the *Smithsonian*, *National Geographic*, *Reader's Digest*, *The New York Times* and other publications. Her most recent book, *The Living Medicine: How a Lifesaving Cure was Nearly Lost and Why it Will Rescue Us When Antibiotics Fail*, chronicled the history of phage therapy and was longlisted for the PEN America Literary Awards.

What Is Intelligence?

*At a church in Italy, we sought to shed an old definition
for one that could save us*

BY AMANDA GEFTER





MARCELO GLEISER RANG THE CHURCH BELL to marshal us inside. The clangor cut across a hushed landscape. We were in the Tuscan countryside on an impossibly green hilltop, nothing but sheep bleating in the distance, and the creak of iron gates, flanked by carved stone lions, at the end of a gravel drive lined with Italian cypress trees.

The church belongs to Gleiser, a Dartmouth cosmologist and author most recently of *The Dawn of a Mindful Universe: A Manifesto for Humanity's Future*. It came with the villa he bought here above the town of Moteroni d'Arbia. Gleiser fixed up the 500-year-old chapel with a dream of turning it into a think tank and named it the Island of Knowledge.

We were here to come up with a new definition of intelligence. The old one, according to Gleiser, won't do. "We have an ideology of infinite growth on a finite planet," he said. "That's obviously not sustainable. What kind of intelligence are we using to create this scenario? That keeps me up at night."

To expand the definition of intelligence, Gleiser brought together cognitive neuroscientist Peter Tse; astrophysicist Adam Frank; evolutionary ecologist Monica Gagliano; philosopher Evan Thompson; technology critic and essayist Meghan O'Gieblyn; and Indigenous scholar Yuria Celidwen.

Inside, the church was small but grand. White stucco walls arched into a vaulted ceiling; colorful rugs were strewn across the terracotta floor. In place of wooden pews were comfortable armchairs. Celidwen, an Indigenous woman of Nahua and Maya lineage from Chiapas in southern Mexico, walked toward the dais, stood in front of the altar and blew into a small clay flute.

Poems would be recited. Tears would be shed. We weren't allowed to wear shoes.

She produced a haunting melody. The scientists were rapt. I could see the earnestness on their faces, and Gleiser's most of all—a belief that whatever was about to happen in that church had the potential to save the world. Suddenly, Gleiser's dog burst into the church and bounded down the center aisle, as if summoned by the song. He stood in front of Celidwen, ears perked at attention and barked. Celidwen repeated the melody.

Celidwen looked around the church, its iconography replete with reminders of colonialism. She asked if we could go outside.

The sun was beating down. Celidwen told the scientists to gather in a circle. I hung back against the church door. Celidwen gestured for me to join, and I pointed at my notebook to say, "Just a journalist. Just watching." She shook her head. Not an option. I set my notebook on the grass and found a place to stand.

Celidwen handed us each a dried leaf, which she produced from a small pouch, then told us to taste it. "Let it explore your palate," she said. I pretended to comply but palmed mine, wondering what it would be like to be the kind of person who puts a strange thing in their mouth just because someone tells them to. Maybe it would be nice, I thought. To feel so open and part of something. She asked us to lay down in the grass, join hands, close our eyes. My little leaf fluttered to the ground.

This was not going to be a typical scientific conference. Which I suppose made sense when you're trying to overhaul typical scientific ideas. Poems would be recited. Tears would be shed. We weren't allowed to wear shoes.

I tried my best to keep an open mind.

INTELLIGENCE IS USUALLY UNDERSTOOD as the ability to use reason to solve problems, skillfully wielding knowledge to achieve particular ends. It's a linear, deductive, mechanistic view, born in the Renaissance (which bloomed not far from here) and fully embraced by science after a workshop not so different from this one.

In 1949, at Manchester University, a computer scientist, a chemist, a philosopher, a zoologist, a neurophysiologist, and a mathematician got together to debate whether intelligence could ever be instantiated in machines. One of the participants, Alan Turing, inspired by the discussion, went home and wrote up his "imitation game," now known as the Turing test, where a machine is dubbed intelligent if, through text conversation alone, it can fool us into thinking it's human.

Seventy-five years later, we've got chatbots acing the Turing test, and science conceiving of brains as Turing machines. Is it possible we're missing something? The roboticist Rodney Brooks once lamented our "intellectual



ANCIENT WATERS

Indigenous scholar Yuria Celidwen enjoys thermal water that once powered a medieval mill in the Tuscan village of Bagno Vignoni.

essence of living intelligence. Living intelligence, Thompson said, isn't so much about solving problems as it is about defining problems in the first place.

Problems arise for living systems precisely because they need to keep on living. And they do that, Thompson explained, through "autopoiesis," the biological process of self-creation and self-maintenance by which a cell or organism builds itself, over and over again, through its inter-

cul-de-sac, in which we model brains and computers on each other," each model a mirror reflecting the other, with no understanding of how understanding comes in.

Inside the church, I could feel Gleiser's urgency as he launched the discussion. Could the world agree on a new definition of intelligence before our collective stupidity destroys us?

In the usual way of thinking, one starts with a problem, applies intelligence, then arrives at a solution. That works great for Turing machines, whose intelligence comes down to the ability to follow explicit rules, or algorithms. But when we turn around and apply it to ourselves, administering IQ tests like Turing tests in reverse, designed to see how well a human can perform like a machine, we fail to capture the

actions with the world. Unlike a living creature, nothing matters to an AI, because the AI is not built out of the consequences of its own actions. When nothing matters, nothing is a problem. Nothing *means* anything. "People call large language models 'stochastic parrots,'" Thompson said. "But I think it's insulting to parrots."

If problem-solving is linear, autopoiesis involves a circular causality that loops through the brain, body, and world. It's for this reason that the group agreed on a rather radical claim: To understand intelligence, we need a new view of causation. Or rather, an old one, one that goes back to Aristotle's "final causes" before they were ousted from the scientific method by the likes of Francis Bacon and Galileo. Tse, the neuroscientist, called for a "relational



PLANT WISDOM Ecologist Monica Gagliano's experiments have shown that plants learn from experience, altering their behavior in response to environmental cues from their past.

view of causation"; Thompson referred to it as the causality of life, in which, as Kant wrote, "parts reciprocally cause and effect the form of the whole."

Thompson, drawing from work by the anthropologist Gregory Bateson, explained how the old view of intelligence "forces a linear structure onto the non-linear and entangled networks that make up the complex systems of the body and its relation to the environment, which Bateson calls the 'total mind.'" When we lose sight of those circular feedback loops, we become blind to the consequences of our actions—how they react back on ourselves and reverberate through the world. If machine-like straight lines are intelligence, then Bateson's total mind is something more like wisdom.

O'Gieblyn told a story of how, when she was 13 years old, she set out on a quest to become wise. For three years, on the advice of a pastor, she read daily from the Book of Proverbs. "Did this exercise make me precociously wise?" Not

STEVE PAULSON

“People call large language models ‘stochastic parrots.’ I think it’s insulting to parrots.”

exactly. The trouble, she explained, was that at 13, she hadn’t lived much. “It seems that the wisdom of aphorisms can only be grasped in hindsight, after one has arrived at their truth through the ordinary hell of trial and error.”

When an artificial neural network trains on data, O’Gieblyn asked, or is told what’s right and wrong by a human supervisor, does that result in intelligence? “Or is that a little too much like a 13-year-old girl thinking she can become wise by underlining her favorite proverbs in her study Bible?”

Aphorisms, algorithms, Thompson said, they’re “late to the party.” They are small bones fossilized from the messy body of lived experience. Take that experience away, and the intelligence goes with it.

I SKIPPED THE MORNING Qigong ceremony the next day and slipped into the church as the group was resuming discussions. Frank suggested that the planet exercises its own form of intelligence. “I’m not talking about consciousness,” he clarified. “Intelligence.”

It’s an idea that goes back to James Lovelock and Lynn Margulis’s Gaia theory: the proposal that the biosphere (the sum total of life on Earth) is self-regulating. Just as a cell’s metabolic network produces the components of which it’s made, including its membrane, which allows it to persist, life on Earth,

according to Gaia, is an autopoietic-like network that produces itself and the atmospheric boundaries that allow it to continue existing.

“Gaia was a really important idea,” Frank said. Until the New Agers got a hold of it in the 1970s. Frank showed a photo of “neopagans” Oberon and Morning Glory Zell-Ravenheart, dressed in full hippie garb, crouching beside what appeared to be a small unicorn. “Yes,” he said, “that’s a unicorn. Somebody took a goat and glued a horn to the top of its head.” (It wasn’t glue; Oberon, a self-declared wizard, had patented a surgical procedure exclusively for unicorn production.)

But the fact remains that for 4 billion years, the geosphere and biosphere have been shaping each other’s evolution. Early in Earth’s history, Frank explained, the biosphere was “immature”—it drew matter and energy from the geosphere but didn’t have enough interconnections to act back on the planet in ways that would stabilize the system, so it was always at risk of running itself into the ground. Then came the “great oxygenation event”—which wasn’t so much “great” as “nearly disastrous.” Some 2.4 billion years ago, life invented photosynthesis and flooded the atmosphere with oxygen, which was poison to most living things at the time, leading to a mass extinction and sending the climate plummeting into an ice age.



LIVING INTELLIGENCE

Unlike machines, philosopher Evan Thompson explains, living systems exhibit intelligence through circular feedback loops that produce and maintain themselves.

Luckily, the system righted itself. Life invented a new form of metabolism, one that used oxygen, which in turn covered the energy cost of multicellular life. Oxygen in the atmosphere formed the ozone layer, which shielded life from fatal ultraviolet radiation. Life and Earth, they were finally in balance—the biosphere had matured.

“Now if there’s a solar flare,” Frank said, “and sunlight increases by 10 percent, certain bacteria will start spawning, generating chemicals which then flow out into the atmosphere, changing the Earth’s reflectivity, which brings the temperature back down.” It’s exactly the kind of autopoietic circular causality that is, according to Thompson, the mark of living intelligence.

But now, on top of the biosphere, we have the “technosphere”—the sum total of human activity; technology, transport, communications systems. And the technosphere, Frank, is “is not self-maintaining, it’s the opposite. It’s degrading the conditions that it needs to survive. What do we have? Another couple hundred years?”

Gagliano offered up a new perspective: Maybe the only path to a mature technosphere is to re-engage with the biosphere we seem to have forgotten. “Throughout my 15 years working with plants, it has

STEVE PAULSON

become ever so clear that we are engaging with a lot of intelligence,” she said. “And we’re so fixated on our own intelligence and capacity to solve problems that we don’t realize we don’t have to do it alone as a human species.”

Gagliano told the group that her plants talk to her. She clarified: literally. They tell her things she doesn’t know; offer design specs for her experiments. Sometimes they’re snarky. Sometimes they’re sweet. Surely they can advise us, if we ask for their help.

Tse, the neuroscientist, seemed circumspect, and determined to hang on to a shred of human exceptionalism. He insisted that when we talk about the intelligence of other animals, let alone of plants, we don’t really know what we’re talking about, because we have no way of knowing what they think or want.

Just then, Felix, the dog, trotted over to the church doors and barked. Frank walked over and opened the door; the dog happily ran outside. “Empathy is how we know,” Frank said, walking back to his chair. “We don’t have to model it intellectually. We feel it with our living bodies.”

WE ALL TOOK A FIELD TRIP to float in Etruscan thermal baths. “When the plants talk to you,” I asked Gagliano as we trudged through a garden to get to the ancient hot springs, “are they speaking in English? In Italian?” She laughed, as if she’d been asked this dumb question many times before and slipped into the rippling pool with the other scientists. I hung back, watching from the sidelines, the scent of sulfur stinging in my eyes.

Later, back in the church, Gagliano spoke about attention. Science’s idea of paying attention, she said, is to come to a pre-given reality with pre-given boundaries and try to describe or represent it, passively, as mere observers. “But this denies the porousness of the body,” she said. “The *feeling* body is not only irrelevant but antithetical to science.”

I started to understand: The point wasn’t whether the plants were talking; it was that she was listening. And when you listen—not

passively, but porously—you begin to hear astonishing things.

Gagliano described an experiment where she and some physicists wired up spruce trees in a forest in the Dolomites to record their electrical signals. They were monitoring the signals when the trees suddenly synchronized their behavior—first the oldest trees, then the younger. Fourteen hours later, there was a solar eclipse.

According to Gagliano, it was as if the oldest trees remembered the signs—the strange tugs of gravity coming from the celestial alignment—and spread word through the forest to take action in advance, to preserve their water. As Gagliano put it, the older trees were saying, “Hold your hydraulic potential!”

Their sample size was too small to draw grand conclusions, but the results were enough to raise grand questions. Questions you wouldn’t ask if you assumed from the start that trees can’t remember or learn or communicate; if you assumed, that is, that intelligence resides in singular brains alone.

During a coffee break, I asked Celidwen. “In your culture, do people think of the mind as in the head?” She let out a hearty laugh. “Of course not.”

Later, when we were all sitting in a circle wrapped in blankets in the unheated church, she told a story.

“When I was a child, my assimilated teacher told me that I wasn’t very intelligent,” Celidwen said. “I went home to my dad and asked him, what is intelligence? He said, I don’t know what your teacher meant, but we think of intelligence as the way we nourish our relationships. The better you are at caring for all our siblings”—our fellow humans, animals, plants, the elements of the Earth—“the more intelligent you are. My grandmother understood all the gossip of the birds, when to plant, when to cultivate, when to harvest, and the language of the water and wind. She only studied until the first year of elementary school, but she was profoundly wise.”

Our old definition of intelligence forces us to act as if we live in a small world.

Something seemed to click in the room. The questions we'd been asking about who has intelligence—birds? ferns? machines?—had been utterly beside the point because intelligence is not something one *has*. It's something one participates *in*, the tangled feedback loops that make up this whole interwoven planet. We're intelligent if our participation keeps the system healthy, and stupid if we eat through it like a cancer.

Gleiser's wife, Kari, a trauma psychologist, showed the group a video of the famous "still face experiment" to demonstrate what happens when relational intelligence breaks down. In the video, a psychologist instructs a mother to interact normally with her baby—talking, cooing, making silly faces. Then, she's told to freeze. The baby tries to engage the mother; the mother doesn't react. The baby tries harder. Nothing. The baby begins to wail. It's hard to watch. You feel it in your chest. You feel for the confused baby, of course, but you feel worse for the mother, forced to deny all her own instincts, to stop her body from doing what it *knows*, responsively, responsibly—intelligently—to do.

BY THE END of the week, I began to feel it in *my* chest: Science had gotten intelligence wrong.

Back at that 1949 workshop, Turing found himself debating the scientist and philosopher Michael Polanyi. What Polanyi argued at that meeting was that human intelligence has a component that can't be stated in propositional terms, and therefore can't be mechanized as AI, a "tacit knowledge," he called it, saying, "We know more than we can tell."

Thompson had said AI functions in "small worlds"—realms of narrowly defined problems in search of formal solutions, purposeless billiard games of cause and effect, lacking context and meaning and care.

Our old definition of intelligence forces us to act as if we live in a small world. A world where trees can't remember eclipses and the planet is a dumb, spinning rock. Only we know—somewhere deep in our biology, in our total mind—that the world is so much bigger. That we are so much bigger. Yet we stare at it, still-faced, hanging back against the church door.

"Those leaves," I asked Celidwen, "the ones you gave us to put in our mouths on the first day—what were they?" I was kicking myself for having been so stubborn then.

"It's from a native plant of Coelhá, where I was born, that is called *mummun*," she said. "In the Indigenous lore of the area, it is used in



ARISTOTLE IN THE BRAIN Neuroscientist Peter Tse argues for bringing Aristotelian causes—agency and purpose—back into science.

ceremony to bring people together, to enhance “heart relationships,” or relationships based on emotional intelligence.”

It occurred to me that if intelligence is participation in big, messy cycles of activity and self-regulation that loop through the whole system of life on Earth, then our job is not really to join in. Our job is to realize that we’re already in. That we exist in relation from the start, linked through gravity, oxygen, language, through lines of evolution and adaptation that stretch back billions of years. That we know this—not as one knows an aphorism, but tacitly and totally. That the real work is to trust in the intelligence all around us, in all the things we know but can’t tell.

As the final meeting wound down, I found myself alone in the church with Gleiser. He was gazing at one of the paintings on the wall, *The Temptation of St. Anthony*. Artists throughout history, including Hieronymus Bosch and Michelangelo, have depicted St. Anthony being seduced by Satan to indulge in wealth and glory. But this version, by Italian painter Rutilio Manetti, is unusual. “The weird thing is that the devil is wearing glasses,” Gleiser said. “It’s reason tempting faith.” ☺

AMANDA GEFTER is a science writer and the author of *Trespassing on Einstein’s Lawn*.



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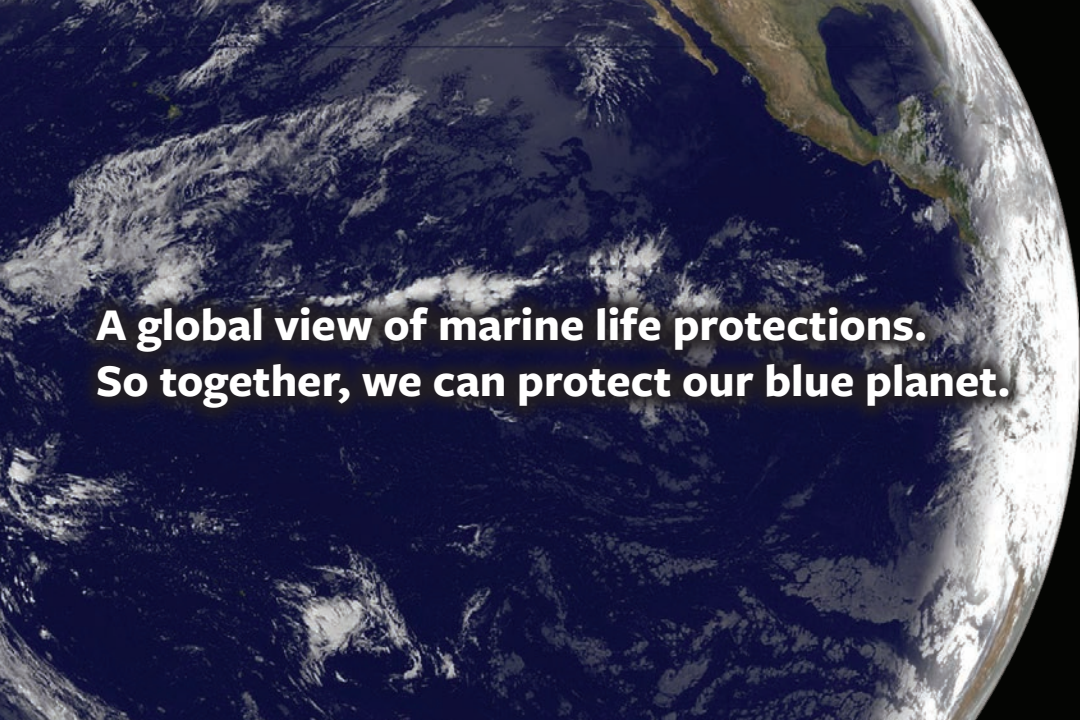


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TALES OF WONDER AND TURMOIL

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Findings

A mother is 4.6 percent more likely to give birth in the same month she was born.  Half of all beef consumed in the United States is eaten by 12 percent of adults.  The playing speed of a metal guitarist directly correlates with his intrasexual competitiveness but not his mating success.  Scientists advised against consuming hypersexual zombie cicadas infected with psychoactive fungus.  A metal scar on the surface of the white dwarf WD0816310 indicated that it has cannibalized other bodies in its orbit.  Dwarf rock-wallabies were found to have unusually large teeth. "If I were a vegetable," said a skull-shape researcher, "I would not mess with a pygmy rock-wallaby." 

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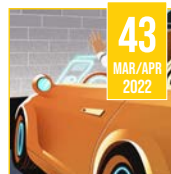
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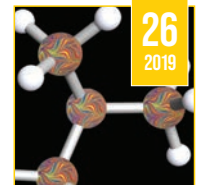
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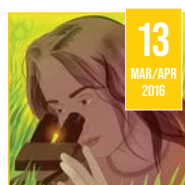
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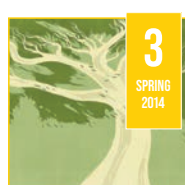
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ALAN LIGHTMAN

The physicist and author on scientists as humans and building public trust

INTERVIEW BY NICK HILDEN



HOW SCIENCE SHAPED THE AMERICAN IDENTITY

In the 19th century, there were a number of scientific projects led by the National Geological Survey, the telegraph, railroads, and a number of other big projects associated with a young country exploring and improving. Science and technology were really part of the growth of the United States, and became part of our self-identity as a country of entrepreneurs, risk takers, adventurers. Until very recent years, that was part of our national identity. Google and Apple and the laptop computer, the transistor—all of that came out of the U.S. But if we start making the U.S. an unpleasant place for entrepreneurs to work, then all of that talent is going to leave our country. And it already has started. I'm not so concerned with our competitive position relative to other countries. I don't think that we have to be the best at everything. But I do think that our own standard of living and quality of life is going to diminish if we lose our talented scientists.

THE VALUE OF EXPERTS

Once we start departing from evidence-based thinking, we will be going on assumptions that are not validated by experiment. Climate change, depleting natural resources of our environment—we need bona fide scientists working on those problems who understand them. We need chemists and physicists and climatologists working on those problems. Without them, we're going to go back to the dark ages. We're really going backward now in so many areas, but the mistrust of scientists is one of the areas that can have a domino effect.

BUILDING TRUST

I'm a member of a small U.N. committee advising the Secretary-General on how to restore trust in science. We're instituting local community forums in different countries, addressing local problems like polluted drinking water or grazing disputes, and showing how science helps solve those problems. That shows on a very local, community level how scientists work for the benefit of society. We need a lot more of that kind of thing.

THE EMOTIONAL LIFE OF SCIENTISTS

Scientists are human beings—we have the same emotions, jealousies, ambitions, and passions as other people. Most scientists I've known are competitive, and that's a good thing because it gets people to do their best. Individual scientists can become emotionally involved and cling to pet theories even after they're disproved, but inside the community we are very hard on each other. If someone claims a result and wants to win a Nobel Prize, I'm going to try to reproduce that experiment and prove them wrong. That's the spirit of science. ☺



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