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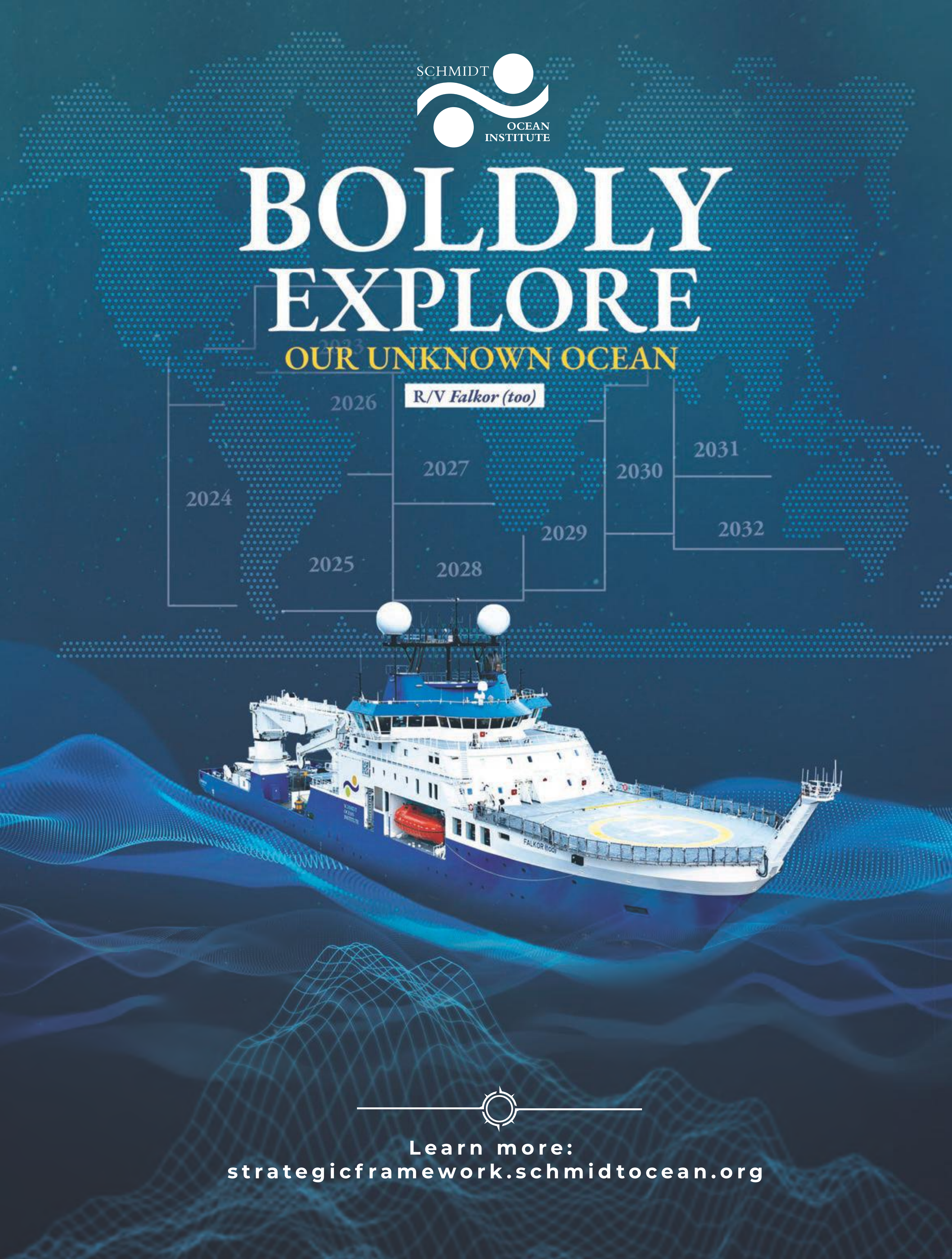
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Coming of Age in the Himalaya

BY KEVIN BERGER

IN THIS ISSUE'S COVER STORY, "The Last of the Fungus," author Zhengyang Wang (Yang) writes that he feels like he has slipped into the plotline of Rudyard Kipling's *Kim*. Yang, a biology student, has been in the Himalaya trying to fathom the ecology of a caterpillar fungus. He has scoured the mountains with secretive fungus hunters, met shifty dealers, and visited labs where scientists are attempting to synthesize the fungus, prized for its reputed healing powers; it's known as "Himalayan Viagra."

Yang takes up residence in a monastery in Kathmandu, Nepal. He wants to brush up on his Tibetan and pick up whatever information he can from the fungus dealers there. Nearby is the Russian Embassy. At the monastery, Yang suspects people are watching him with a wary eye, as if he was the wily Kim, who goes undercover on behalf of the British government to investigate Russian agents in India. Finally, Yang convinces his monastic neighbors that he is "more of a quixotic wanderer than a serious security threat."

Yang, 32, is now a postdoctoral fellow at Harvard. "The Last of the Fungus" is his first long journalistic feature and can be read as his own coming-of-age story. The fungus is essential to Tibet's economy and a big part of Yang's quest is to help the villagers whose lives depend on it. Yang grew up in Chengdu, China, tucked in the eastern Himalaya. His mom works in forestry and agriculture and his dad is a mushroom forager. When he was growing up, his parents took him on field trips to across the Himalaya. "This part of the world is always very close to my heart," Yang says.

Yang says he did come of age during research. "It taught me that science is a human endeavor," he says. "Now I always keep that in mind when I develop my research questions, and hopefully that has made me a better biologist. "Many of the organisms I study have deep human impact. On the other hand, the process of doing science is a messy entanglement with other scientists and many stakeholders. When I'm bogged down by details of research, I usually think about people I meet and how my research could potentially impact their livelihood, and that gives me motivation to work."

During seven years of traveling to and from the Himalaya, from 2016 to now, Yang learned that staple of growing up: patience. "I could have been more patient seven years ago and more understanding of alternative ways of making a living," he says. "My younger self tended to project what I think is correct onto other people's lives. I really didn't think caterpillar fungus, from a medicinal point of view, makes much sense, and I tried to convince other people of that. Now, although my stance on the issue remains the same, I don't try to convince anyone about how they should live their lives."

Although, when Yang looks back at his seven years in the Himalaya, not everything is about grand life lessons. "I can't even believe it myself," he says. "But I spent most of my 20s studying caterpillar fungus!"


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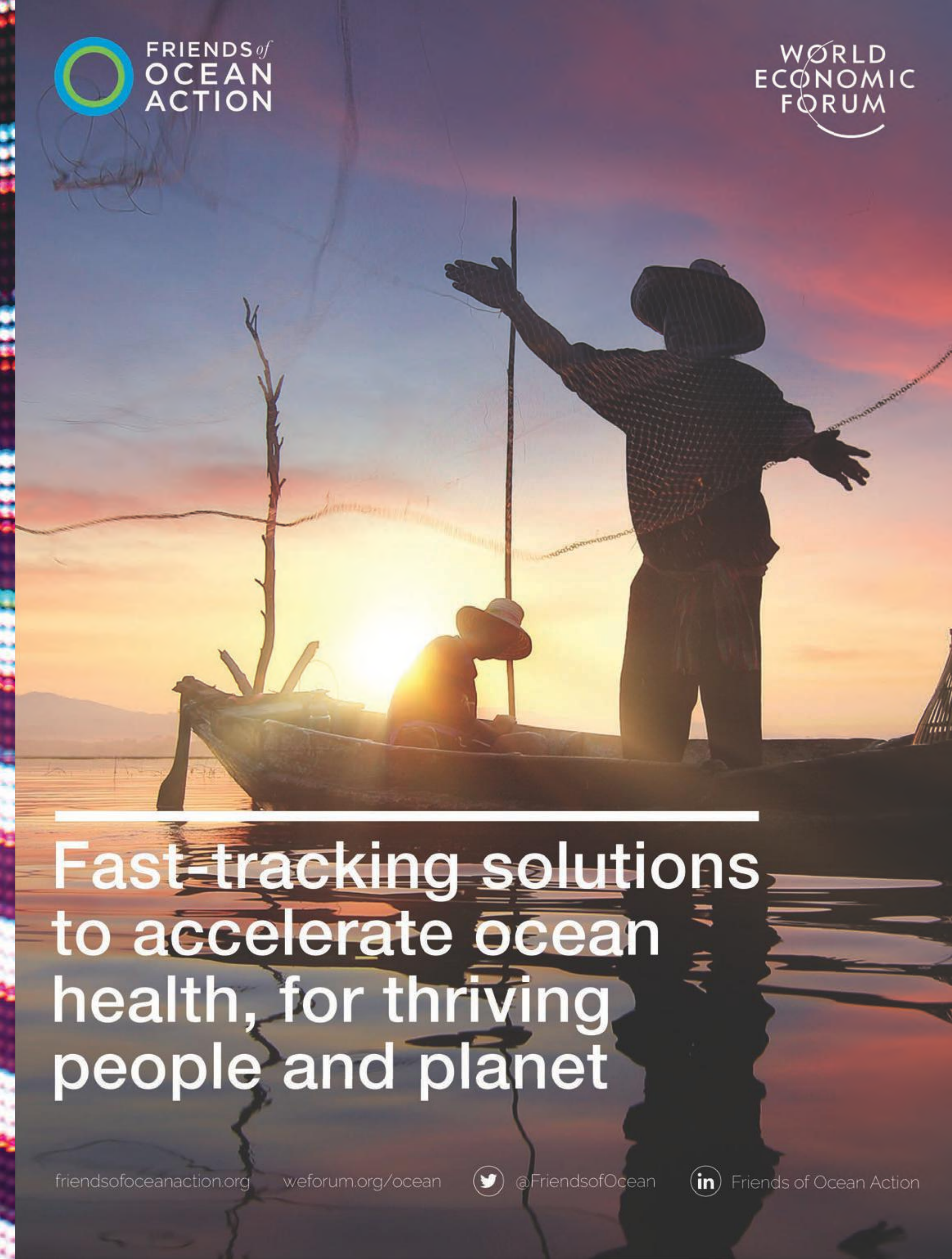
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THE PORTHOLE

Short sharp looks at science

TECHNOLOGY

A Scientific Breakthrough in Noise Reduction

THE MORE PEOPLE that live on our planet, the harder it becomes to avoid noise. Small surprise that noise reduction is a booming business. Your AirPods might have active noise canceling, but do they have a plasmacoustic metalayer? Maybe they soon will.

At the moment, you can either use materials that absorb or scatter noise, such as earplugs or foam mattresses. Or you can have active noise cancellation that works by creating a signal that destructively interferes with the one you want to get rid of. The problem with both of those approaches is that they don't work for all frequencies or only work for steady signals, like the constant or continuous hum of an engine or air-conditioning unit.

A group of Swiss researchers has now created a prototype for an active noise canceling device that uses plasma. In a paper in *Nature Communications*, published in May, they explain how they used nothing but ionized air and wires to deaden sound. Their device works very much like noise canceling headphones, but it doesn't have a membrane, or a flexible material that vibrates in response to electrical signals—instead it moves the air directly. This works much faster and over a larger range of frequencies.

It works like this. The prototype device has two metallic electrodes that conduct electricity separated by a tiny air gap. That's the metalayer. The researchers use a microphone to pick up sound and calculate the required voltage to cancel it. The voltage will differ depending on

ALEUTIE / SHUTTERSTOCK

The ions stop the air motion and thereby the noise.

the kind of sound the device needs to eliminate. When one electrode receives power, it ionizes the air nearby with the appropriate voltage, converting the molecules from neutral to charged, which pushes them around. The ions stop the air motion and thereby the noise.

In their experiment, the researchers used a device just about three centimeters thick to absorb sound waves from 20 to 2,000 hertz almost perfectly.

That's really impressive. But we must remember to think about the potential impact of this new technology on our social lives. If it wasn't for the noise, maybe we'd never get to speak to our neighbors.

—*Sabine Hossenfelder*

Now, researchers are learning that the sense of smell is critical as a marker of brain disease and health.

Over the past decade, loss of smell—known as hyposmia—has emerged as an early indicator of several neurodegenerative disorders, according to a recent *International Journal of Molecular Science* review of 20 papers. The high prevalence and early onset of smell loss, along with the development of sensitive olfactory tests, has raised interest in it as a diagnostic tool for Parkinson's disease and Alzheimer's disease, in particular. But loss of smell also afflicts people with Huntington's disease, multiple sclerosis, and mild cognitive impairment. Catching these diseases early by testing for powers of smell could give patients a head start on neuroprotective and disease-modifying therapies.

The connection between odor detection and brain health makes sense. Our sense of smell begins in the nose and then proceeds directly to the olfactory bulb at the base of the brain. It's the first sensory structure we have that provides direct contact with sensory stimuli and environmental pathogens in the air. Experimental evidence suggests olfactory bulb neurons play a key role not just in the loss of smell but also in the early stages of brain disease.

Researchers at the University of Padova in Italy are looking at how the sudden smell loss characteristic of COVID-19 connects with Parkinson's disease. Viral infections, like COVID-19, and regional inflammatory processes may trigger defective proteins to aggregate, a feature of Parkinson's, and lead neurons to subsequently degenerate, the researchers hypothesize. Certain psychiatric diseases are also associated with smell dysfunction: Schizophrenia patients have shallower nasal cavities and smaller olfactory bulbs than healthy individuals, as well as other nasal abnormalities that Alzheimer's patients also experience.

NEUROSCIENCE

Loss of Smell May Be an Early Sign of Brain Diseases

IT'S SUMMER IN SAN DIEGO, California, where I live. When I walk down the street, I can smell the delirious musk of jasmine clinging to the air. My nose picks up the languid smokiness of briquets burning on barbecues, taking me back to decades of yard parties. But given the heat wave descending on the city, the garbage is also throwing off a sickly stench, hinting at decay. These odors are all good signs.

We have long known that smell has potent connections to memory and emotion, as the endurance of Proust's proverbial madeleine moment attests. In fact, the limbic system, including the amygdala and the hippocampus, is responsible for processing not just memory and emotion, but also smell. While Western culture has generally relegated the sense of smell to the lowest rank since the time of Plato, some hunter-gatherer groups such as the Semaq Beri of the Malay peninsula have more words for smells than for color hues.

LIGHTSPRING / SHUTTERSTOCK

Not everyone with smell loss will develop brain disease. The acuity of our sense of smell declines as we age but follows a different trajectory from that of some other cognitive and perceptual abilities. While short-term memory peaks at age 25, for example, the power of the nose peaks in middle age, around age 40, and then gradually begins to slip. Age-related loss of smell is greater in men than women, and women have a higher total number of olfactory bulb cells than men—at least 50 percent more, on average, research suggests.

Aside from its connection to neurodegeneration, smell is also a powerful marker of overall health and mortality risk. In one longitudinal study of 1,162 healthy older people (without dementia) the mortality rate over a four-year period was 45 percent for those with the lowest baseline olfactory test scores, compared to 18 percent for those with the highest scores, even after controlling for age and other factors.

The power of the nose peaks in middle age, around age 40.

It is surprisingly difficult to know when we have lost our sense of smell: About 70 percent of people living with a loss of smell don't realize it until they're tested. (If you're curious, you can take the "Smell Test Challenge," sponsored by the Michael J. Fox Foundation, a scratch-and-sniff exercise to see how well you perform—and potentially be invited to join a research study.) There may be more truth than we realized to the saying, "Follow your nose."

—*Kristen French*

ZOOLOGY

A Third of North America's Birds Have Vanished

FOR WEEKS, ADAM SMITH had been crunching the raw data from more bird statistics than anyone had ever tried before—13 different bird counts and millions of radar sweeps. Suddenly he heard the musical chime that tells him his results are ready. He leaned across his desk, surrounded by enough high-powered computers to heat up his entire office, and stared at what could only be an impossible conclusion: Over the past 50 years, his calculations found, a third of North America's birds had vanished. "Well, that can't be right," he thought. "I must have made a mistake somewhere."

ANDERS GYLLENHAAL

Smith, one of the hemisphere's top specialists in bird populations, just sat for a while in his cluttered cubicle at the Canadian Wildlife Service, which was decorated with caribou antlers, a musk-ox skull, and early drawings from his twin boys. Then it dawned on him. "This would be a massive change, an absolutely profound change in the natural system," he said. "And we weren't even aware of it."

Up until that point, counting the abundance of individual birds throughout the entire continent was impossible. At any given time, many species number in the tens of millions in North America—adding up to billions of birds—and they're constantly on the move. But the science of bird study was advancing, and a close-knit group of scientists was experimenting with using radar imagery, satellite photos, and citizen science to add precision to the dozens of conventional bird counts done for groups of species.

The computation Smith had just finished that day in May 2019 combined individual population estimates for 529 bird species, from the most common sparrows and robins to rarities hardly ever seen. When Smith pulled these estimates together and adjusted each for its degree of certainty, the findings came down to a single ski slope of a chart. It showed a precipitous drop in nearly all these species in every part of the continent. At the bottom sat four lone digits—2.913. That's the number of breeding birds in billions that had disappeared since the early 1970s. He had documented an accelerating churn of seasonal losses that slowly took their toll on the abundance of birds. And it translated to an astounding third of the adult birds that not long ago filled North America but now are gone. The hardest hit were grassland birds, down by more than 50 percent, mostly due to

ANDERS GYLLENHAAL

the expansion of farms that turn a varied landscape into acres of neat, plowed rows. That equates to 750 million birds, from bright yellow eastern and western meadowlarks with their incessant morning songs to the stately horned lark with black masks across the male's eyes and tiny hornlike feathers that sometimes stick up from their heads. Forest birds lost a third of their numbers, or 500 million, including the compact, colorful warblers and speckle-breasted wood thrushes that sing like flutes. Common backyard birds experienced a seismic decline. That's where 90 percent of the total loss of abundance occurred, among just 12 families of the best-known birds—including sparrows, blackbirds, starlings, and finches. There's been relatively little research on these species, and there's no sense of urgency when resources are already stretched thin for so many other birds in more dire need.

The possibility of such losses was too startling to share with his colleagues until Smith checked every step of his calculations, particularly since he'd never attempted this analysis before. "It always takes a couple of times to get these numbers right," he said. After a day and a half of painstaking scrutiny, Smith realized there was no mistake. "I was speechless. We've lost almost 30 percent of an entire class of organisms in less than the span of a human lifetime, and we didn't know it."

—Anders Gyllenhaal & Beverly Gyllenhaal

From *A Wing and a Prayer: The Race to Save Our Vanishing Birds* by Anders Gyllenhaal and Beverly Gyllenhaal.

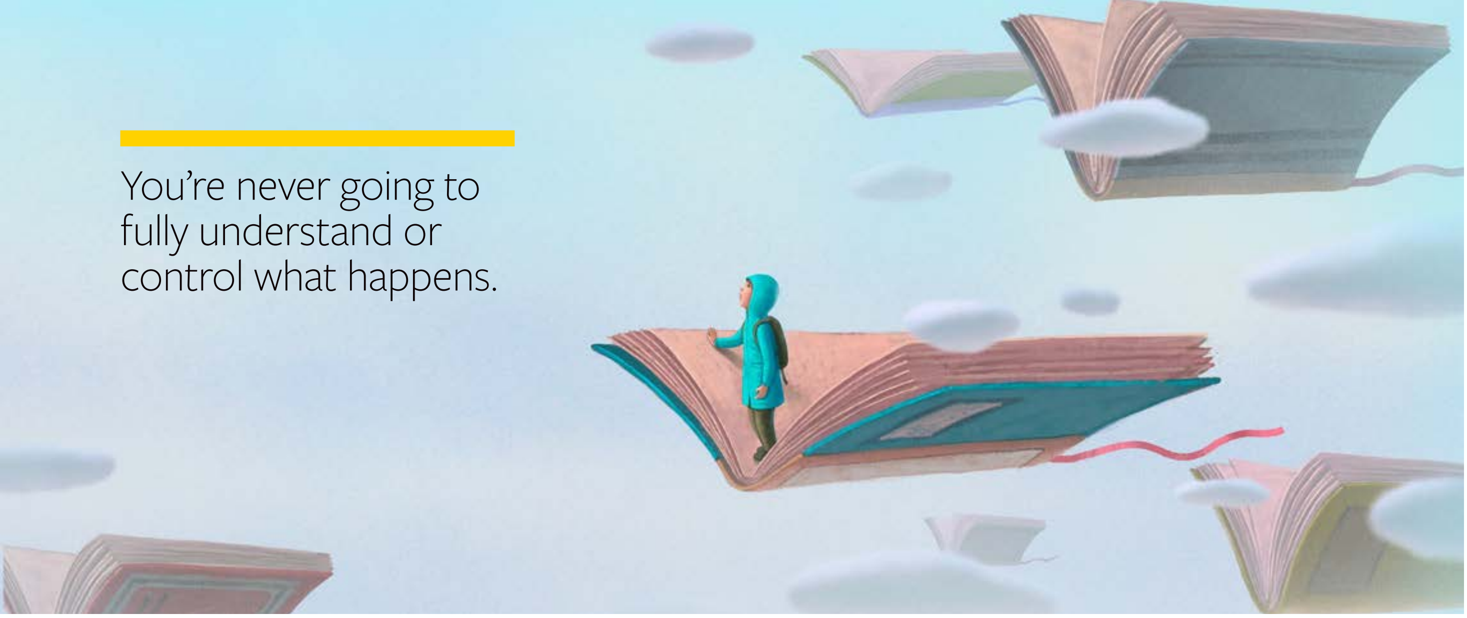
ANDERS GYLLENHAAL

PSYCHOLOGY

Does Dream Inception Work?

WILL DOWD LOST HIS ABILITY to read over a decade ago. He has a condition called binocular vision disorder, which makes it difficult to coordinate his eyes. Words drift across the page, getting tangled up in one another, and the pain of trying to extract meaning from the resulting quagmire gives him debilitating migraines. Dowd had been an obsessive, devoted reader—a poet and MIT-trained science writer who lived mostly in the world of paper and ink—so the condition left him feeling exiled from himself.

The act of dreaming was the only other time Dowd felt the readerly combination of total absorption and flight, and so he wondered: Could there be a connection between the two? Could reading be a kind of lucid dream? He recalled hearing about a device called the



> You're never going to fully understand or control what happens.

Dormio, a targeted dream inception device developed at the MIT Media Lab, and wondered if it could help him simulate the reading experience. A grant from the Woodberry Poetry Room at Harvard University enabled him to test this theory out on himself over the 2022-2023 academic year. The resulting project is called DREAMFALL.

How do you use the Dormio to simulate reading through dreaming?

I listen to recordings of the first lines of poems that are unfamiliar to me and use those as seed phrases to push my dream in a certain direction. After I listen to the first line, I go to sleep, and when the Dormio wakes me up, I write down every sensory detail I can remember, every leap of logic. Then I listen to the rest of the poem, and one of my favorite things is to see how they intersect. More often than not, there are some strange intersections, and I think that may say something about the shared human imagination. But I've also found that the seeds have only a glancing impact on the dream. It's never literal. You can often find traces, but what I'm discovering through the process is that dreams naturally do not like to be controlled. They live in the realm of the trickster.

Can you give me an example?

I think I remember this most vividly because it was my first one, but I listened to a line of a poem by an Irish poet, Padraic Colum. The narrator is a man living in a tower, and the first line is about seagulls flying around the tower. In the dream that I had, I was a child on a beach and I confronted this magician, who was showing me all kinds of Christopher Nolan *Inception*-style tricks that he could perform—drawing an invisible circle in the sky so that suddenly you're seeing into another place where it's snowing. At the end, there was an invitation to follow, like a magician's apprentice, leaving the regular world, like I was getting my letter to Hogwarts. When I listened to the rest of the original Irish poem after writing this all down, I found it was about a young girl going to the tower to meet an older poet, who was very much like the magician, an older kind of mentor figure. But in that case, the poet refuses to be the mentor. He turns the girl away and recommends that she take flight on her own. That mentor relationship was not in the seed phrase, so it's just an example of some of the synchronicities that come up. I don't try to get too mystical about that because I'm more interested in creative dialogue, but it was a fascinating start to the project.

Has this approach satisfied your longing for the experience of reading?

So far it feels as though those two experiences of reading and dreaming do diverge in a very fundamental way. And it has to do with the fact that when you are reading, even if you're immersed in the book, you have an understanding of yourself as a reader and the world and experience as being crafted through your imagination, but ultimately from the foundation of the author. In dreams, the author is occluded and mysterious, and you don't know who's behind that curtain. And so this idea I had that maybe I could become a new

JORM SANGSORN / SHUTTERSTOCK

type of writer, a specialist in dream seeds who would design these perfect lines or phrases that could grow into beautiful reading-type experiences inside other people's dreams, like a haiku-dream bonzai-sculptor—that is falling away. The dream has its own agenda and there can still be an interaction there, but you're never going to fully understand or control what happens. The subconscious hand sculpting these dreams will always be inaccessible to the part of me that's speaking right now, the ego.

Is that a disappointment?

Not at all. I think it's healthy to learn some humility. I have less fear now that the dream world is gonna be somehow gentrified or paved over and turned into a strip mall, that our dreams will be incubated with product advertising through sleep apps. It's a relief to realize that there's a territory of the human experience, of the mind, that is untameable and will always remain out of the reach of our gadgets.

—*Kristen French*

ASTRONOMY

When Stars Twinkle, They Make Music

WITH ENOUGH DETERMINATION, people can turn almost anything into a musical instrument: a blade of grass, an array of water glasses, a field of flowing sand dunes in Abu Dhabi, or a system of stalactites. But why stop there? Evan Anders, a fluid dynamics researcher at Northwestern University, and his colleagues just transformed an entire star into a musical instrument.

The researchers' formal goal was to vibrate a star and listen to the response, as a way to study its inner workings. Lacking godlike powers, Anders and company could not conjure an actual, physical star. They had to make do with a model of a giant ball of gas and plasma, 15 times as hefty as the sun, and pump simulated waves through its layers. Then they indulged in a dose of whimsy, using their stellar instrument to crank out some celestial tunes: a passage from Gustav Holst's *The Planets* and a snippet of "Twinkle Twinkle Little Star."

"Dynamically, we want to know what's happening inside massive stars," Anders says, because they exert a tremendous influence on everything around them. High-mass stars die in colossal supernova explosions that seed interstellar space with heavy elements. The oxygen in Earth's air and the silicon in the ground originated in these stars. Without them, you would not be here.

The dramatic life and death of a massive star is controlled by events deep in its core. That's where fusion reactions synthesize new elements and keep the energy

CDDESIGN.CO / SHUTTERSTOCK

flowing—until the reactions fail, the outer parts of the star blow to bits, and the inner part collapses into a neutron star or a newly minted black hole. Outward appearances reveal only a little about what's going on. To get the full story, you need to explore far beneath the surface. Sound turns out to be an excellent tool for doing just that.

Stars are musical, ringing nonstop in response to the fusion energy pouring out of their cores.

Astronomers have discovered that stars are highly musical, ringing nonstop in response to the fusion energy pouring out of their cores. When all those good vibrations wriggle to the top, they make the star flicker slightly. That innate "twinkling" provides outward evidence of the processes generating the waves hundreds of thousands of miles below: sound translated into light.

The challenge for Anders and his team is that stars play many tunes all at once. They wanted to pick out one specific tone, the rumbling of convection in the core. Waves from the core could reveal crucial information about the processes that cause massive stars to blaze and, eventually, self-destruct. So Anders and his colleagues fired up their computers, strummed the cores of their virtual stars, and listened carefully for that single, telltale sound. "It's like we put our star in a recording booth and measured the waves coming out of the center," he says.

The resulting jam session, recently published in *Nature Astronomy*, offers a remarkable cross-section examination of a giant star, showing how sound waves travel through regions that we could never observe directly. One frustrating thing that Anders learned in the process is that stars are not well designed for high-fidelity listening. When he played the sound of the core through the star's overlying layers, he found that the waves got horribly muffled, "like if you put a band in some really bad venue," he says.

By the time the waves from the core reach the surface, Anders determined, they are so feeble that they cause the star's brightness to vary by just one part in 1 million. Today's telescopes aren't accurate enough to pick out that one wave pattern from the cacophony of other sounds that stars generate; we can't eavesdrop on stellar cores just yet. But now we know what to look for with tomorrow's telescopes.

Anders and his team also created a wonderfully detailed model of how sound waves travel through a star. That model could be useful to other researchers—or, in principle, it could allow anyone to play music through a star. Maybe their stellar instrument could become an online app, I suggest. "That's actually a really good idea," Anders laughs.

The acoustics might be terrible, but who could resist hearing Prince's "Baby I'm a Star" on the largest (yet) soundstage in the universe?

—*Corey S. Powell*

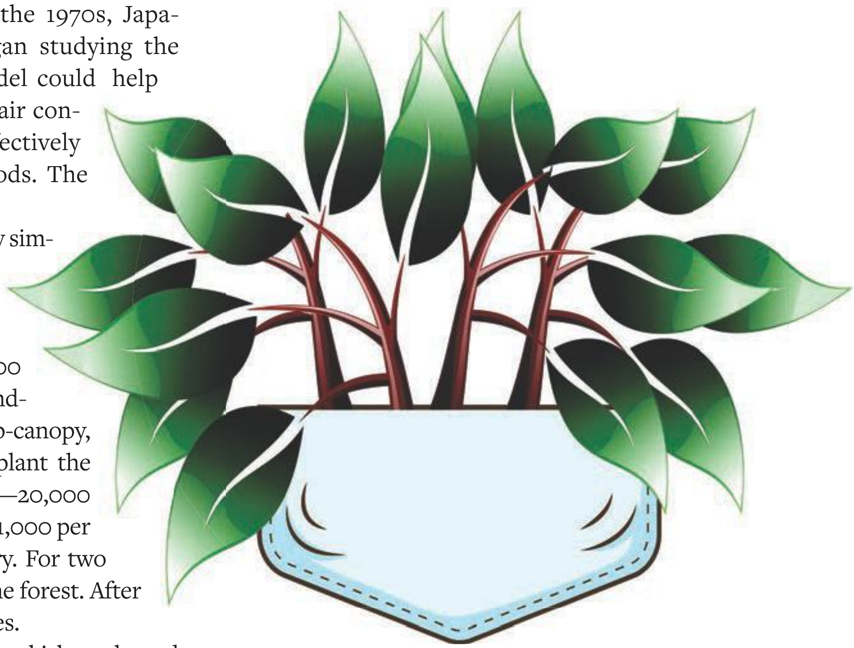
ENVIRONMENT

Pocket Forests Are Coming to Town

A **COUPLE OF YEARS AGO,** a crew of volunteers planted 1,400 trees in a former landfill the size of a basketball court at Danehy Park in North Cambridge, Massachusetts. Suddenly a space that might hold no more than 10 basketball players was overtaken by a dazzling crush of saplings. The micro-woodland, which contains 32 native species, was the first example in the northeastern United States of what is known as a Miyawaki forest.

When you think of a forest, you might imagine a sea of pines stretching across a craggy mountainside or groves of cottonwood, willow, and poplar blanketing a valley in green—trees as far as the eye can see. But many urban conservationists have been turning to a much tinier model, one borrowed from Shinto shrines in Japan.

These shrines often honored spirits and gods of the forests, so the temple grounds, in turn, hosted miniature stands of trees. Sometimes called "pocket forests," these sacred groves were ultra-dense and highly biodiverse. In their attempt to recreate the complexity and beauty of natural forests, the temple gardeners tended to reproduce the ecosystem relationships that make natural forests resilient. In the 1970s, Japanese botanist Akira Miyawaki began studying the shrine forests and decided the model could help rewild urban environments and repair contaminated sites more quickly and effectively than other standard forestry methods. The Miyawaki forest was born.



The Miyawaki method itself is fairly simple: Conservationists are tasked with improving the soil on the designated site with organic material and microorganisms. They then identify 50 to 100 species endemic to the particular landscape in four categories: canopy, sub-canopy, understory, and shrubs. Next, they plant the trees in dense and random mixtures—20,000 to 30,000 per hectare rather than the 1,000 per hectare typical of commercial forestry. For two to three years, they water and weed the forest. After that, the forest is left to its own devices.

Over the past few decades, Miyawaki has planted more than 750 Miyawaki forests in Japan, Malaysia, and South America. The Miyawaki model has also been popular in Europe, with projects like Urban Forests in Belgium and France, and Tiny Forest in the Netherlands. In the U.S., conservationists only recently began planting Miyawaki forests, including stands in Seneca, South Carolina, and Maysville, Missouri. The Cambridge effort was organized by Ethan Bryson, an architect by training and an expert in soil biology. He launched National Urban Forests in 2016 to promote the Miyawaki method after watching a TED Talk by entrepreneur and former industrial engineer Shubhendu Sharma. Sharma, who met Miyawaki himself while working at Toyota in India, has turned the Miyawaki forest into a global business through the company he founded called Afforestt.

In his TED Talk, Sharma declares the Miyawaki forests pack a real conservation punch, growing 10 times faster, getting 30 times denser, and containing 100 times more biodiversity than a "conventional plantation" forest. Other advocates have claimed that Miyawaki forests can grow into mature ecosystems in just 20 years—compared to the range of 70 to 200 years it can take a natural forest to regenerate on its own—and that they can support up to 20 times as many species as non-native, managed forests.

Some say pocket forests are an exercise in greenwashing. Earlier this year, *Mongabay* reported the pocket forests sprouted in Japan when Miyawaki was hired by Nippon Steel to spruce up its factory site with a forest. In 1973, Japan required that big factories devote 20 percent of their land to greenery. Miyawaki was then hired by some of Japan's biggest car, utility, and chemical companies. Earlier this year, Indian eco-gardeners Fazal Rashid and Somil Daga wrote an op-ed entitled, "How Mr. Miyawaki Broke My Heart" in an Indian publication, *Science: The Wire*. Rashid and Daga argued that the Miyawaki method often fails to replicate native forests and may destroy other healthy ecosystems. They pointed out the practice is often a way for small businesses to make a quick dollar through corporate social responsibility budgets.

Some scientific evidence for the Miyakawi method is emerging. One small study from the Netherlands and another from Italy support claims of rapid growth and high biodiversity. In the United Kingdom, scientists have set up a monitoring program to measure ecosystem benefits. As the data roll in, Miyawaki, now in his early 90s, continues to plant trees.

—Kristen French

TASNUVA ELAHI; WITH IMAGES BY RHEO AND RALFDESIGN / PIXABAY

The BigPicture 2023 World Nature Photography Finalists

NOW IN ITS 10TH YEAR, the California Academy of Sciences' renowned BigPicture Photography Competition celebrates some of the world's best photographers and the year's most striking images. Judged by an esteemed panel of nature and conservation photography experts, the competition's winning images and finalists highlight Earth's biodiversity and illustrate the many threats that our planet faces. Each photo, in its own way, inspires viewers to value and protect the remarkable diversity of life on Earth. Below, we present the grand prize winner and a few of our personal favorites from this year's competition.

—*Krista Langlois*

BACKYARD FRIEND Grand Prize winner. *Photo by Corey Arnold.*

WAITING FOR LOVE Finalist; winged life category. *Photo by Audun Rikardsen.*

THE SECRET LIFE OF UNDERWATER HIPPOPOTAMUSES: Finalist; aquatic life category. *Photo by Mike Korostelev.*

The Last of the Fungus

A young scientist's quest to transform a dying way of life

BY ZHENGYANG WANG
PHOTOS BY THE AUTHOR

IN EASTERN TIBET, high in the Himalaya, Tenzin stopped at a cliff edge. He lit another cigarette. In front of us, Mt. Gongga dazzled in spring's morning light, a dizzying 24,800 feet above sea level. Tenzin is not his real name. His perilous occupation—collecting and selling caterpillar fungus—is fraught with competition and secrecy, and I didn't want to put him in jeopardy with the local authorities.

Tenzin (a common local name meaning "holder of Dharma") had reluctantly agreed to show me how to find the treasured fungus. He was in his mid-30s and generally taciturn. But his growing dissatisfaction with my ability to keep up on the trek began to show in his furrowing eyebrows. It was 2016, and I was a first-year doctoral student in search of a thesis. I, too, grew up in this part of the world—my hometown in the Sichuan lowland was only a day's drive away. But I was naive enough to think that training on an elliptical machine was adequate preparation to hunt caterpillar fungus in person. Whenever I fell too far behind, Tenzin sat down and smoked a cigarette in ostensible boredom.

This parasitic fungus took over the bug's body and commandeered its brain.

We retreated from the cliff and trekked along steep grasslands. Tenzin stopped at a cluster of dry plant stalks no less than a few inches tall and gestured to me to come over. He pointed to a brown stroma—a bundle of spore-bearing fungal tissue. It looked like a rusted nail sticking up in the soil.

The previous summer, our quarry was an unsuspecting insect spending its larval caterpillar days—on its way to emerging as a ghost moth—in what should be the safe embrace of the earth. Through a process that had remained mysterious, it picked up an unfortunate infection: an insidious and wily fungus called *Ophiocordyceps sinensis*.

This parasitic fungus took over the bug's body and commandeered its brain, maneuvering the caterpillar into the perfect place, just below the surface of the soil, before consuming it from the inside. At just the right time in the spring, the fungus blasted a stroma out of the caterpillar's head and up from the soil.

Tenzin took out a pocketknife and plunged it into the ground next to the stroma. He excavated the "caterpillar" part of the booty. It was eerie: the mandible, complex eyes, three pairs of prolegs—characters I encountered in my entomology coursework, now real, half-covered in soil and dangled under the stroma. Even the exoskeletal segmentation was clear. But the ex-caterpillar was twisted, a sign of suffering in its previous life; the fungal stroma looked sinister and triumphant. Tenzin protectively wrapped the caterpillar fungus in a home-sewn pouch.

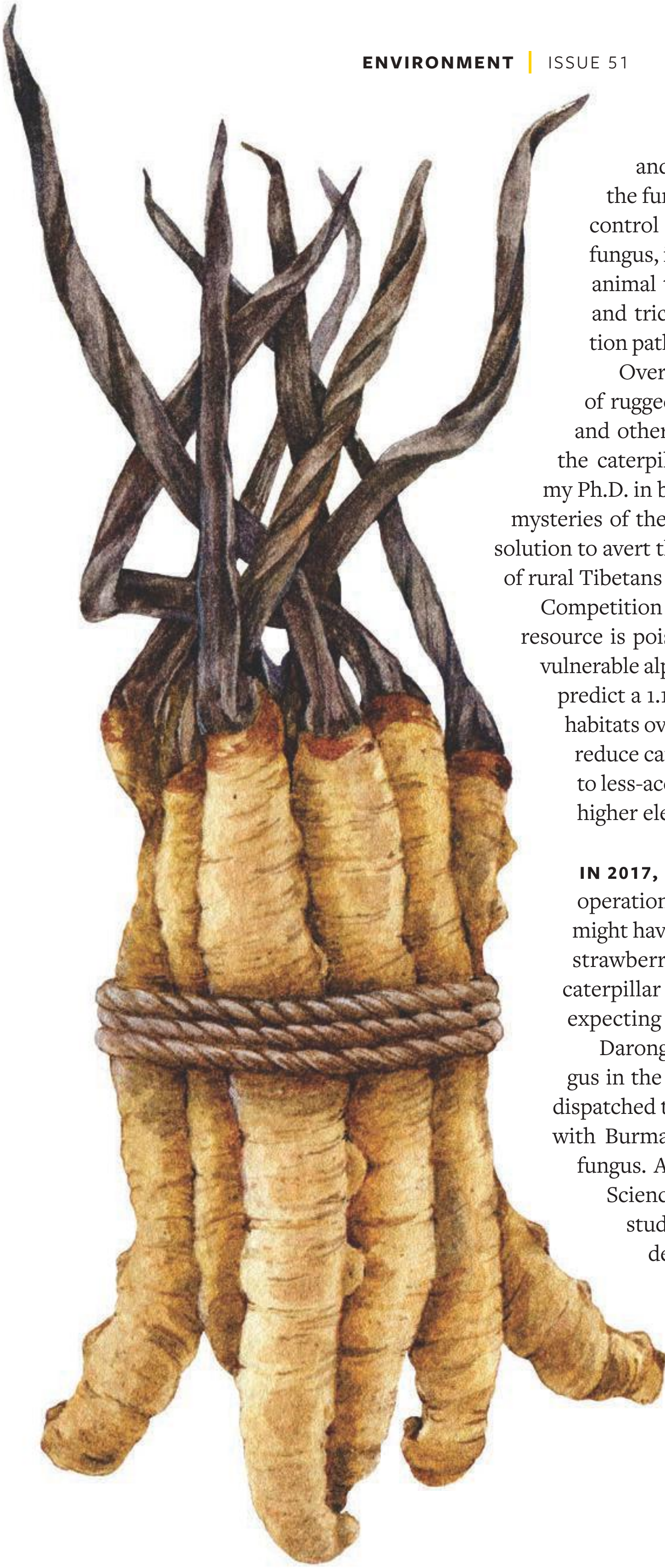
Before sunset, we found more than 30 caterpillar carcasses. We arrived back at his village after nightfall, and Tenzin sold them all to a middleman for $300. Two weeks of unusually good days like this would bring in roughly the average income for a Tibetan household for an entire year.

The fungi would now begin a journey that left the villagers like Tenzin behind. It would trickle through village-level middlemen to the city of Kangding, eastern Tibet's once prosperous tea-horse trading post. From there, they would be brought to the inland metropolis of Chengdu, China, meeting streams of other caterpillar fungus from other networks that crawl over the entire rugged range from northwestern India to the Qinghai-Tibetan Plateau. Most would be dispersed across the coastal Chinese megacities, where they are sold in herbal medicine markets, high-end restaurants, and caterpillar fungus specialty shops that have the ambiance of exclusive wineries.

Throughout Asian history, caterpillar fungus has been celebrated to have medical and aphrodisiacal powers. Today it's known as "Himalayan Viagra." Most modern scientific experimentation has failed to demonstrate any lasting medicinal potency in the fungus, but its roots in culture and tradition have proven nearly impossible to break. Demand for it is insatiable.

To feed this hunger, some 100,000 kilograms of dry caterpillar fungus are harvested along the Himalaya each year.[1] This means more than 300 million caterpillar fungi are hand-picked annually from the world's rooftop. Market price of caterpillar fungus equates to a full tenth of Tibet's gross domestic product—more than its mining and other industrial sectors combined. With this amount of money, stakes are high; not far from Mt. Gongga, armed conflicts have broken out between rival villages for access to good caterpillar fungus habitat.

IN A VANISHING HAYSTACK
Local caterpillar fungus collector Tenzin treks near the Yanzigou glaciers, more than 12,500 feet above sea level, to seek the the telltale stroma of the fungus. The glaciers are melting, and the land is warming, threatening this precarious industry.



One way to prepare for this ecological and economic doomsday is to try to cultivate the fungus, putting the vagaries of nature under control and, potentially, at scale. But caterpillar fungus, it turns out, is not a simple crop to sow, or animal to husband. It is a complex and intimate and tricky organism, whose life cycle and infection pathways have eluded scientists for centuries.

Over the course of seven years and thousands of rugged miles, I intermittently followed Tenzin and other treasure hunters on the fevered trail of the caterpillar fungus. Along the way, I worked on my Ph.D. in biology at Harvard University, probing the mysteries of the caterpillar fungus. I hoped to uncover a solution to avert the disaster I saw looming for the millions of rural Tibetans whose lives depended on it.

Competition for this limited but naturally renewable resource is poised to escalate. Caterpillar fungi grow in vulnerable alpines of the Himalaya and Tibet. Scientists predict a 1.1 degree Celsius temperature rise in these habitats over the next decade, which will significantly reduce caterpillar fungus yield, and force collectors to less-accessible, more dangerous, and more fragile higher elevations.

IN 2017, I DROVE to a humble-looking agricultural operation in eastern Tibet's mountain valleys. It might have been mistaken for yet another roadside strawberry farm; in fact, it was an experimental caterpillar fungus breeding center. Darong Yang was expecting me.

Darong had first learned about caterpillar fungus in the 1970s when, as a college student, he was dispatched to a military encampment near the border with Burma, another hotspot for the cold-adapted fungus. After working at the Chinese Academy of Sciences and a long career in insect taxonomy studying host moths of caterpillar fungus, he decided to go commercial.

Earlier in the year, his breeding center had struck tentative gold: He cultivated one kilogram of caterpillar fungus. It took Darong his entire academic career to figure out the pieces of a viable breeding scheme. He bred the ghost moths,

ANITAPOL / SHUTTERSTOCK

Caterpillar fungus has been celebrated to have aphrodisiacal powers. Demand for it is insatiable.

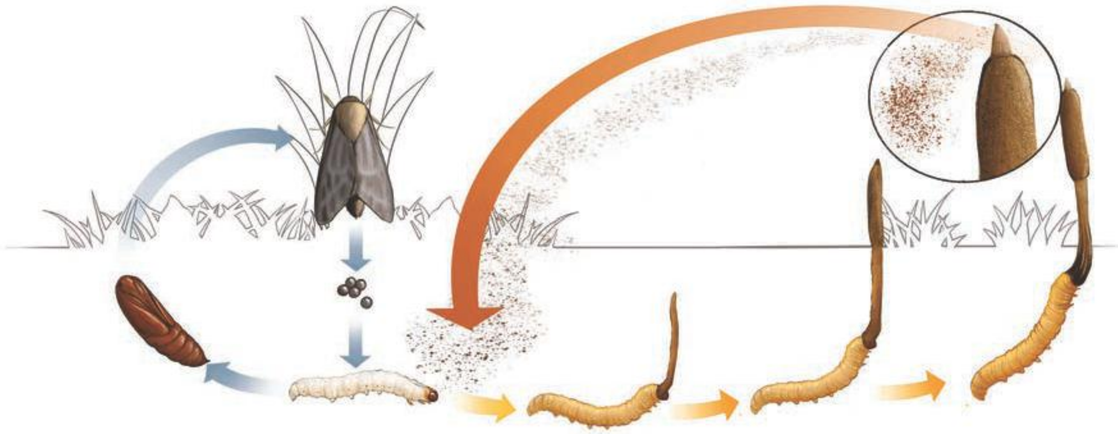
collecting the eggs—some 300 for each female moth. These eggs are isolated in a pupal growth chamber and hatched under strict, sterilized conditions. Once the millions of caterpillars are just the right age, a few are selected to become breeding moths, and the rest are treated to a shower of O. *sinensis* spores. Then Darong prays that his caterpillars are infected. His prayers are rarely answered.

That came as a surprise to Darong—and most anyone else tracking this fungus. In their natural habitat, about 10 percent of underground ghost moth caterpillars are infected with O. *sinensis*. Bringing caterpillars into captivity and assaulting them with a salvo of highly concentrated spores resulted in 10,000 times fewer infections. It took Darong about 5 million caterpillars to produce that one kilogram of caterpillar fungus. It was enough to generate interest, but far from enough to fundamentally change the livelihood of millions of people.

And Darong's is one of the most successful operations. In the past decade, some 20 caterpillar fungus breeding centers have sprung into existence across China, many government-funded or university-affiliated. None has achieved an infection rate even close to that effortlessly accomplished in nature.

Each year, breeding centers have to cycle through hundreds of millions of ghost moth caterpillars, like lab rats, to test new infection strategies. However, most centers did not invest in the technical expertise and infrastructure to maintain a sustainable host moth population like Darong does. Instead, they rely on a more immediate way to source their test subjects: digging them out of their grassland homes.

As someone studying entomology, I knew there was a crucial difference between harvesting caterpillar fungus and harvesting caterpillars. Infected caterpillars are essentially dead ends; collecting them is harvesting something that is, in a sense, already gone. Live caterpillars, on the other hand, are essential for population renewal—and thereby, caterpillar fungus generation. Because these live caterpillars are so multitudinous



THE CYCLE OF A ZOMBIE Ghost moth caterpillars grow underground until they are ready to metaphorize into their winged adult form. But about one in 10 of them somehow becomes infected with a parasitic fungus. The fungus takes over the insect's body, steering it close to the surface, where it then eats the bug from the inside, fueling its own growth until it blasts a stroma skyward, dispersing spores into the environment, in search of new caterpillars to infect.

(in the right habitat), uprooting them also means decimating vast areas of pristine vegetation that is already under strain from rapid climate change.

Being so essential to the region's economy, these breeding efforts are backed by major cash. Breeding center representatives will arrive in a village and offer high prices for live caterpillars, leading to a local "caterpillar rush" on their habitats. By the next year, villagers will see a devastating decrease in their caterpillar fungus yield. By then, of course, the cunning representative would be long gone.

My academic research in the lab, half a world away, kept leading me back to one vexing question, one that required me returning to the source for the answer: How, exactly, were the ghost moth caterpillars becoming infected in their natural habitat? This knowledge could increase yield and reduce the back-breaking, and sometimes deadly, work collectors like Tenzin had to endure.

Later in 2017, I headed back to Mt. Gongga with my questions, but Tenzin had no time for my grand gibberish. Coinciding with my visit, a breeding center representative was offering villagers $1 for each live ghost moth caterpillar exhumed from the Yanzigou—the highest yielding habitat around Mt. Gongga. It seemed like the entire village was digging in, shoveling bucket loads of tundra soil and picking out anything that wriggled. This time, Tenzin did not bring the home-sewn pouch as he would for fungus collection; he carried a big shovel and plastic water bottles for his live captures.

Armed conflicts have broken out for access to good caterpillar fungus habitat.

In twilight, dozens of people crowded into a dimly lit shack behind the local convenience store, where the representative counted live caterpillars by hand, tossing them into a large water bucket. The congregation was hushed (and I would like to think, slightly mollified—though I couldn't discern anyone's face in the shadows). The cash-only transaction was swift. I stayed to observe the full count: 20,000 live caterpillars dug out of the soil in a single day.

In the course of a few weeks, I saw villagers turn the delicate montane ecosystem, with its succulent and radiant flowering plants, upside down like an apocalypse in fast motion. Alerting the forestry official was useless (and it was never a good idea to meddle with village politics). Instead, I preached biology to anyone who would listen—drawing life cycle diagrams to show that there won't be caterpillar fungus next year if they dug out all the caterpillars now. But what eclipsed reason that summer was a tragedy of the commons. Tenzin told me that if they didn't dig, villagers downstream would beat them to it.

All the while, these tens of thousands of live caterpillars would go on to breeding centers only to likely elude fungal infection. Their lives were, by a twist of still-mysterious ecology, spared from that fate. But their futures augured an increasingly bleak outlook for the village.

BACK IN THE UNITED STATES, in the lab, I began to formulate an idea as to why the efforts to infect caterpillars in captivity were failing. Having grown up collecting insects and keeping quite a few of my own "trade secrets" about their whereabouts, I grokked that habitat is more than a bug's residential address: It's where it eats, mates, and encounters predators and prey; it's the tangled bank and the web-of-life. Extracting a species from its habitat is an oxymoron, like asking us to live without eating and breathing.

RAN AND SACKED In an effort to cultivate valuable caterpillar fungus, breeding centers offer quick cash for live ghost moth caterpillars, leading to a rush on their delicate alpine habitat.

Parasitism, I reasoned, also depends on habitat. When a zombie ant, for instance, is possessed by a fungus (*Ophiocordyceps unilateralis*), the ant will climb to just the right spot on a tree and clamp its jaws on the underside of a leaf. From this advantageous position, the fungus pushes a stroma out of the now-deceased ant's head and rains spores onto more unsuspecting ants below. The fungus' reproductive success depends on the abundance of its hosts. There is no dearth of ants in the rainforest, so showering them with airborne spores makes evolutionary sense.

But this is not the case for *O. sinensis*, whose infection target, the caterpillar, prefers to live about a foot underground—and spore density of *O. sinensis* is negligible this deep in the soil. So how did symbiosis with a host playing hard-to-get arise in the first place?

What if plants, I thought, were the true hideout of *O. sinensis*? Caterpillars are, in a way, just squishy, salad-loving automatons. This hypothesis explained how the caterpillars were becoming infected: Caterpillars evolved to eat plants, and what better way to infect them than by poisoning their food? The hypothesis also explained why infection in captivity had been so elusive. Removing wild vegetation in captivity cut off the evolved pathway of fungal infection.

To test this hypothesis, I returned to Mt. Gongga in 2018. I managed to talk Tenzin into being my guide again—I promised not to slow him down. This time, we had to trek farther up the glacier to find caterpillar fungus, since most habitats had been decimated the previous season in the mad rush. Villagers were visibly moody about the decreased fungus harvest. Before my arrival, one of them, looking for a better yield, risked the steeper side of the valley, lost his footing, and fell to his death. Most villagers believed karma was responsible. Following the accident, village elders removed wooden planks across ravines to close off the mountains. I, having played Cassandra the previous year, was granted the last passage.

Amid the grasslands, my plan was simple. If *O. sinensis* lived inside the plants, I should be able to detect it there. With Tenzin leading the way, I collected 690 samples of leaves and roots from the 27 plant families in the habitat. I then drove them straight to the nearest molecular lab, nearly 200 miles away. I sterilized and smashed each sample for analysis. To study them, I developed molecular "probes" that would only bind to a fragment of the *O. sinensis* genome. Whenever this binding occurred, a beam of fluorescent light shone and could be picked up by a sensor.

Later, I headed back to Mt. Gongga with my questions, but Tenzin had no time for my grand gibberish.

The results were unequivocal: More than one in three of my plant samples contained O. *sinensis*. And after analyzing the ooze from 73 wild-dwelling caterpillars from the same habitat, I found in their guts not one but 11 different plant families they'd eaten that harbored O. *sinensis*. The caterpillars were indeed most likely munching their way to infection.[2]

That meant, I realized, the current attempts to domesticate caterpillar fungus were a futile endeavor. Those millions of displaced live caterpillars, those acres of demolished delicate herbage were all for naught, because captive breeding excludes the main pathway of O. *sinensis* infection: eating local plants.

But another idea began taking shape in my brain, one that would make cultivating the fungus even more difficult. Parasitism is not a static process. Hosts and parasites coevolve. If a speciation event occurs and causes a single host species to diverge into two, its specific parasites would split, too. This can lead to a permanent break between a species and its parasite. If the caterpillars and parasites were in the midst of a wide-scale speciation event, it wouldn't work to randomly pick caterpillars and fungal strains. Every person involved in the breeding efforts, from villagers with their shovels to breeding center directors with their cash, would be trying to start a motorcycle with the wrong key. Maybe, I thought, I could help find the right one.

Taxonomists, including Darong the breeder, had already noticed regional differences in some of the physical characteristics of adult ghost moths. Cutthroat caterpillar fungus traders often cite exoskeletal color and size to vouch for the authenticity and provenance of their products. Coevolution, I realized, could very likely have occurred across this vast habitat, which is roughly the size of Alaska and fragmented by the world's tallest mountains—ideal conditions for speciation by geographical isolation.

Back at Harvard, I started to build molecular phylogenies for the fungus and caterpillar, neither of which had been done at this sweeping scale. While it was relatively easy to extract fungal DNA from dried caterpillar fungus, recovering usable host DNA turned out to be a major hurdle, since much of the arthropod is consumed during parasitization, leaving little insect material to work with. I turned to a

A WORM IN THE HAND
Even the most accomplished breeders like Darong Yang (pictured here) haven't been able to mass-produce caterpillar fungus. But many continue to try.

IN THE WILD Dispersed through trade networks across Asia, caterpillar fungus—"Himalayan Viagra"—has been a precious folk medicine commodity for centuries. But the scale of today's market, combined with accelerating climate change, makes it increasingly unsustainable. And tying the livelihood of millions of Tibetans to the caterpillar trade is a brewing disaster.

technique called hybrid enrichment, which was first applied to sequencing ancient Neanderthal genomes from degraded samples. If the protocol worked with prehistoric bone fragments, I figured, it could work with dried caterpillar fungi. I spent a year isolating and amplifying the DNA in my lab. Patience was key: I learned to time defrosting reagents just so, to inhale and exhale at just the right moments while pipetting, to establish order among the hundreds of plate wells. Eventually I had a working method, and fragmented pieces of caterpillar genome could be restitched together.

It was time to take to the road again and collect caterpillar fungus across the vast Himalaya.

IN SPRING 2019, I arrived at a monastery in Kathmandu, Nepal. I wanted to brush up my Tibetan and glean information from local caterpillar fungus sellers and collectors. One of the caterpillar fungus shops I frequented was next to the Russian Embassy, where I motorcycled back and forth after my afternoon language drills. For a while, rumors along the plotline of Rudyard Kipling's *Kim* started to circulate among my peace-loving monastic peers. Was I some kind of undercover agent? But my persistent explanation—*I'm here to study how zombie caterpillars evolved*—eventually left them with no doubt that I was more of a quixotic wanderer than a serious security threat.

Then I took to the terrain, to hunt down these caterpillars across their range—and with them, the steps of their evolutionary dance with a microscopic predator.

My first stop was the foothills of remote Namcha Barwa, the mountain which looms above at 25,500 feet. Reaching these rich collecting sites required traversing dense, subtropical thickets reigned by legions of leeches.

With ounces of my blood left behind, but crucial samples gained, I proceeded west along the Tibetan borderline with Bhutan, Sikkim, Nepal, and northwestern India. I asked villagers to bring me caterpillar fungus (*chong-cao*, *yartsa-gunbu*, or *keera-jhar*, depending on where I asked). Kind stakeholders in this contentious work were usually willing to spare me a few stalks—key data points in the vast trading web spanning almost the entirety of eastern Asia.

I had some trouble on my last stop, though, in the Himalayan ranges of northwestern India, one of the most recent regions to join the "caterpillar fever." Again, I was accused of espionage (the Chinese fighter jets constantly patrolling the distant skyline did not help assuage local worries). Luckily, some collectors happened to be college students trying to make a few bucks during their summer break, and I explained to them my project of making a "family tree" of the caterpillar fungus. They gifted me some of their harvest and befriended me on WhatsApp.

While I was behind the wheel along heart-stopping roads in the high Himalaya, collaborators scoured the northern and eastern edges of the Tibetan Plateau. They delivered caterpillar fungus tied up with foul-smelling yak hair—the way these bounties were packaged centuries ago. I even salvaged a few rare samples soaked in Darong's alcohol concoction (one of two popular ways to consume them in China; the other being stewed in chicken broth).

Back in the lab in Cambridge, samples isolated, enriched, reassembled, and sequenced, a geographical and evolutionary map of these prey-parasite pairs began to come into focus. Among the 93 caterpillar-fungus samples, I found that at least 20 different species of caterpillars and six separate strains of the fungus have coevolved. It turned out that a caterpillar fungus collected in Qinghai is vastly different from one collected in India. Even ones from the eastern and northeastern parts of Tibet, sites within a few hours' drive, fell into separate genetic groupings—incompatible with each others' intimate nemesis. My survey, despite the mileage, covered only a fraction of known caterpillar fungus collection sites. Mountains are biodiversity hotspots, and the true tally of matching host moth species and fungal strains across the Himalaya is likely far higher. In other words: There were so many keys and so many motorcycles—any selection seemed unlikely to match.

This discovery was a final nail in the coffin of current caterpillar fungus breeding efforts. If perhaps dozens of different caterpillar species were each locked in a unique arms race with their own fungal strain, then showering caterpillars with a single fungal strain might be completely useless if they are mismatched. A breeding scheme without consideration of coevolved host-specificity is a waste of time, money, and, in this case, an increasingly scarce natural resource.

In 2022, I published these findings in the *Proceedings of the Royal Society: Biological Sciences*, which would have been impossible without the help of Tenzin and countless local collectors like him.[3] But at a personal level, I had failed them. I had wished to alight on some ecological insight that

More than 300 million caterpillar fungi are hand-picked annually from the world's rooftop.

would liberate them from senseless travail and ecological wreckage; instead I revealed the precarity of living off the land, and the inevitability of the decline of their livelihood if the habitat continues to deteriorate. Even that was a generous impact statement; in all honesty, apart from a few academics (who enthusiastically informed me that *their* insect-devouring fungus was also plant-dwelling), my research was largely overlooked. Live caterpillars were still being excavated in the name of experimentation. Pristine alpine meadows were still being devastated.

This summer, I returned to the region, visiting traders in the Tibetan capital of Lhasa. In the caterpillar fungus boutiques of the old city district, we exchanged butter tea and the ups and downs of this year's business (the price was up again). Since I posted all the genetic markers of caterpillar fungus online, Lhasa traders have braced for a future when they might have to use genetics to authenticate their product. I have stayed clear of any business interests but, even with my Ph.D. work published and wrapped up, I continued to be enthralled by this cultural obsession that props up an entire economy. Some of the traders I interviewed had been dealing caterpillar fungus for three generations, and so had their suppliers in the nearby mountains.

It is possible that caterpillar fungi are still hiding some irreplaceable remedial property—stories abound of medicinal discoveries from traditional or indigenous plants and fungus—but as of now, that science remains null. The industry simply reminds me of the 17th-century Dutch tulip fever and the tragically ongoing ivory craze. I'm in no position to advise local stakeholders on how to make their living, which only leaves me with a spectator's anxiety.

Not all hope is lost for caterpillar fungus cultivation. The interdependent life of the fungus points to a new means to farm it. Breeding centers can't be industrial sow-and-reap operations. They must consider ecological and evolutionary factors. Breeding must be situated where the fungus naturally grows—on undisturbed, high-elevation, microbe-laden soil. Yield will boil down to the land's carrying capacity, to how many caterpillars nature can support, without breaking the equilibrium among plants, insects, and fungi. Breeding centers would look more like conservation land than industrial farms or scientific laboratories. The future of the caterpillar-fungus harvest—a feature of Tibetan culture for five centuries—should look much more like the past. It could again thrive, not in a beaker, but in preserved, existing habitat.

IN A 15TH-CENTURY medicinal text, "An Ocean of Aphrodisiac Qualities," Buddhist lama and physician Nyamnyi Dorje praises the caterpillar fungus in what reads like a hymn:

> It grows in beautiful mountain regions
> On remote grass-covered slopes.
> In the summer it is a blade of grass on a worm
> Similar to the leaf of mountain garlic.
> The flower resembles a silken green sedge.
> The root resembles cumin seed at the end of autumn ...
> It is a faultless treasure of an ocean of good qualities.

Throughout my journeys, I often thought of Nyamnyi Dorje. I imagined him in red robes, kneeling piously to observe the fragile stroma he uncovered one summer evening, jotting his thoughts down on the fragrant pages of a string-bound *pecha*. I long for an opportunity to converse with him and tell him what I've discovered, and what I hope for this region. When I play this scenario in my mind, Nyamnyi Dorje listens patiently, offering more butter tea as I talk. When I finish, he smiles and says only one word: *o-ya*. It means: *good, of course*.

ZHENGYANG WANG is a writer and conservation biologist who uses emerging technologies in molecular ecology and remote sensing to monitor insects across the landscape.

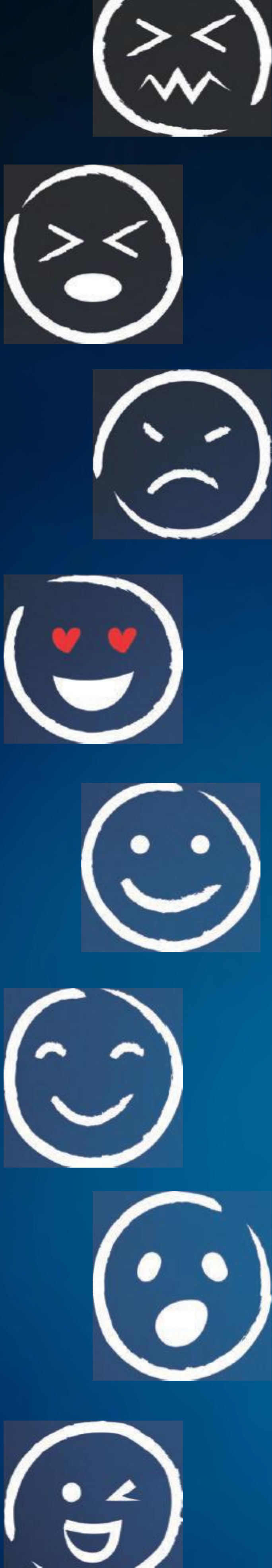
REFERENCES

1. Winkler, D. Caterpillar fungus (*Ophiocordyceps sinensis*) production and sustainability on the Tibetan Plateau and in the Himalayas. *Asian Medicine* **5**, 291-316 (2009).

2. Wang, Z., *et al.* The entomophagous caterpillar fungus *Ophiocordyceps sinensis* is consumed by its lepidopteran host as a plant endophyte. *Fungal Ecology* **24**, 100989 (2020).

3. Wang, Z., *et al.* Profiling, monitoring, and conserving caterpillar fungus in the Himalayan region using anchored hybrid enrichment markers. *Proceedings of the Royal Society: Biological Sciences* **289**, 2021650 (2022).



Your 🧠 On Emoji

It's complicated. And that's good.

BY ALLA KATSNELSON

TWENTY YEARS AGO, Microsoft's instant messaging platform added a new feature: dozens of little icons that users could drop into their messages, conveying happiness, surprise, confusion, or a sheep. Gradually, then all at once, emojis were here: spreading from chat platforms to SMS, email, social media, and—to the chagrin of legions of teachers—even infecting school assignments.

For years, I was an emoji holdout. Embracing the little, cartoonish images felt like transgressing against the virtue of words. To my linguistically traditional soul, raised on Jane Austen and Isaac Babel, emojis seemed cheap and unnecessarily revealing. I resented their creep into written communication, which had long managed just fine, *thank you very much*, with the alphabet.

But just a few years ago, after befriending a colleague whose texts were flecked with these symbols, I had a change of heart. Our daily banter thrived on the emotional zest that emojis added, and on the sense of connection they fueled. Timidly at first, I started to thread them into my digital discourse. Now they're woven into my communication with many people in my life, punctuating a short note or standing alone as a single message, a 💥 or 🔥 or 🌟 as a full-stop reply. What's surprised me most is the palpable joy these flutters of icon-based interaction have added to routine exchanges.

Valeria Pfeifer is a cognitive scientist at the University of Arizona. She is one of a small group of researchers who has studied how emojis affect our thinking. She tells me that my newfound joy makes sense. Emojis "convey this additional complex layer of meaning that words just don't really seem to get at," she says. Many a word nerd has fretted that emojis are making us—and our communication—dumber. But Pfeifer and other cognitive scientists and linguists are beginning to explain what makes them special.

In a book called *The Emoji Code*, British cognitive linguist Vyvyan Evans describes emojis as "incontrovertibly the world's first truly universal communication." That might seem like a tall claim for an ever-expanding set of symbols whose meanings can be fickle. But language evolves, and these ideograms have become the *lingua franca* of digital communication.

THE STORY OF THE EMOJI reaches back further than early instant messaging programs. Before these graphically detailed icons were easy to display, the clunkier, character-constructed emoticon held their place.

Carnegie Mellon computer scientist Scott Fahlman is often credited with codifying these smile-and-wink punctuation constructions. After watching posters in early online bulletin boards get into skirmishes—say, when a poster's sarcasm was misread—he suggested in 1982 that colleagues add a :-) or :-(to indicate their tone. If posters could flag when they were being funny or sarcastic, he figured, readers wouldn't be so easily upset.

Writers and thinkers had, for decades, proposed subbing in punctuation for feelings, though many, it seems, did so in tongue-in-cheek jest. Other early potential emoticons in the wild—such as a ;) in a transcript note describing audience reactions of "applause and laughter" during an 1862 speech by Abraham Lincoln—were likely typesetting errors or examples of looser punctuation norms of the day.

None of these uses took root though until the fertile conditions of the early internet arrived. And as graphical interfaces improved, the contemporary emoji was born.

The emoji didn't initially set out to be a souped-up emoticon. When, in 1999, Japanese artist Shigetaka Kurita developed a first suite of 176 of them for the cell phone company he was working for, most weren't meant to convey a feeling at all. The majority of them were quotidian symbols he envisioned people would toss in occasionally in place of words: a house, an ear, a tennis racket, a fax sign.

It wasn't until 2011, when Apple first made emojis accessible through a dedicated emoji keyboard on their mobile devices (and Android did the same two years later) that emojis truly started going mainstream. By 2015, more than 90 percent of internet users had deployed them, and the *Oxford English Dictionary* named 😂 Word of the Year. Today, the Unicode Consortium, emojis' governing body, as it were, lists more than 3,500 of them.

THE WORD *EMOJI* ITSELF has nothing to do, etymologically, with emoting. It's a blend of the Japanese words for *picture* (*e*) and *character* (*moji*)—unlike *emoticon*, which is an American mix of *emotion* and *icon*. This difference in origin and intention also inflected early scientific research into these new communication tools and their impact on the people using them.

Perhaps the first study of how these visual representations activate the brain was presented at a conference in 2006.[1] Computer scientist Masahide Yuasa, then at Tokyo Denki University in Japan, and his colleagues wanted to see whether our noggins interpret abstract symbolic representations of faces—emoticons made of punctuation marks—in the same way

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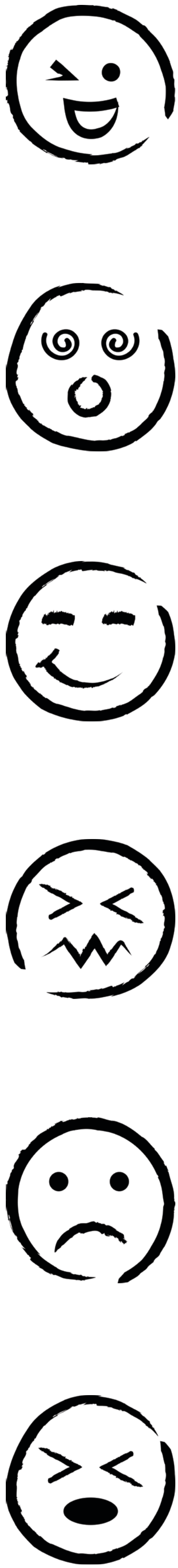

as photographic images of them. They popped several college students into a brain scanning machine (they used functional magnetic resonance imaging, or fMRI) and showed them realistic images of happy and sad faces, as well as scrambled versions of these pictures. They also showed them happy and sad emoticons, along with short random collections of punctuation.

The photos lit up a brain region associated with faces. The emoticons didn't. But they did activate a different area thought to be involved in deciding whether something is emotionally negative or positive. The group's later work, published in 2011, extended this finding, reporting that emoticons at the end of a sentence made verbal and nonverbal areas of the brain respond more enthusiastically to written text.[2] "Just as prosody enriches vocal expressions," the researchers wrote in their earlier findings, the emoticons seemed to be layering on more meaning and impact. The effect is like a shot of meaning-making caffeine—pure emotional charge.

It was surprising that these punctuation faces carried their emotional valence to the reader's psyche without first being recognized as abstract faces. Back then, many researchers assumed people first pieced together the line-and-dot faces and then inferred their expression "as a bottom-up process," Yuasa explained to me via email. But the results suggested that the emoticons were plugging into something more foundational than even face-recognition—hinting that responding to emotion in communication is a primal, even deeper drive.

A few years later, researchers in Australia reported that people were much quicker to grok smiley face emoticons :-) as faces than when the same symbols were typed backward)-: For the lead researcher, Owen Churches, the results

The effect is like a shot of meaning-making caffeine—pure emotional charge.

pointed to our brains' amazing ability to adapt to a quickly changing world.[3] There is no innate neural response to emoticons that babies are born with," he told ABC Australia. "This is an entirely culturally created neural response."

Once the visually richer emojis proliferated, scientists had even more concepts they could interrogate to discern the real-time integration with language, communication, and feeling. And the research quickly became intriguingly nuanced. To wit: Do emojis and words have similar functions when attempting to convey irony? Irony in its most basic form is expressing the opposite of what you mean, to make a point. The incongruity it conveys is so cognitively satisfying precisely because of the layers of drama and meaning it adds to language.

Benjamin Weissman and Darren Tanner at the University of Illinois recorded patterns of brain activity as participants read simple sentences ending with different face emojis—one that aligned with the meaning of a sentence, one that diverged, and one of a wink-face emoji clearly signaling irony.

The cake she made was terrible. ☹️
The cake she made was terrible. 🙂
The cake she made was terrible. 😉

Comparing their findings to previous research on how the brain responds to ironic language, they reported—in their

The interface of language and emotion is where the magic lies.

2018 cheekily titled paper, "A strong wink between verbal and emoji-based irony"—that, as far as the brain is concerned, emojis and words do roughly the same job.[4]

"There's basically a match," says Weissman, a cognitive scientist now at Rensselaer Polytechnic Institute. "As long as there is some sort of irony conveyed and interpreted, the brain response looks pretty similar to the brain response for traditional non-emoji irony." That finding aligns with more recent, still-unpublished work Weissman did with cognitive scientist Neil Cohn at Tilburg University in the Netherlands. There, they probed how the brain responds to reading sentences in which either a word or an emoji matched the expected meaning or had an unexpected meaning:

Her favorite animal is the monkey
Her favorite animal is the 🐒
Her favorite animal is the avocado
Her favorite animal is the 🥑

Here, too, the brain responded to the emojis pretty similarly as to the words, with the expected ones eliciting a brain activity pattern associated with linguistic prediction, and the surprise ones yielding activity associated with processing mismatched meaning.

In a way, Weissman says, it doesn't really matter whether we are calling to mind a concept from a word or an icon. On the whole, for higher-level cognition in which the brain is making complex meaning from inputs it receives, it can integrate all sorts of elements, including facial expressions and tone of voice, he says. And emojis are just another type of this input. "The meaning-making process can probably operate on a level independent of the modality itself," he says.

🐒 🥑 🤷‍♂️

BUT OF COURSE, anyone who has wielded emojis knows they are doing something more than just colorfully, jauntily standing in for words. Like their 41-year-old cousins, the emoticons, they are doing heavier lifting, too. Their ability to convey emotion does a complex dance with language. For Pfeifer, this interface is where their magic lies.

"Emojis have this ability to make the same words seem more emotional or less emotional—to seem alarming versus completely fine or joking even," she says. These are important social functions, she adds. "Through our switch to using a more text-based communication we lost this additional layer of meaning that emojis can now provide."

Our species and our many spoken languages emerged in the frothy cauldron of in-person communication, steeped in tone of voice, volume, facial expressions, gestures, posture, knowing glances. Even as writing forms began to emerge, such as cuneiform more than 5,000 years ago, for the majority of history their use remained largely official—government,

Positive emojis say, "hey, I'm listening." Negative ones have a very different effect.

business, religious. Interpersonal, social, cohering communication was still in-person, and often by necessity; as recently as 1960, less than half of the global population could read and write, and even in Austen's era of the seemingly ubiquitous romantic epistle, only about half of English people older than 14 years could have penned or read a letter.

But as we stepped into the brave new digital world, the written word has taken over much of daily social and collegial correspondence. Texts and direct messages rather than social calls or phone calls. And work meetings or calls now often transmuted into dashed-off lines of keystrokes on Slack or Microsoft's Teams.

As they say, nature abhors a vacuum, and emojis seem to have arrived at a time when a new communication niche needed filling. "The way we communicated when we all started texting or emailing seemed to be deprived of something that emojis seem to fill," Pfeifer says.

She and her colleagues were also interested in the ways in which different emotion-evoking emojis impact social dynamics in their coloring of written statements. They found that happy emojis, such as hearts and smiling faces, added a general emotionally positive boost to a message, though not in any terribly specific capacity. Instead, these pictorial cues served more as bids of connection.[5]

"Positive emojis are like a blinking light on a recording device," she says. "Maybe we send this type of emoji to say, 'hey, I'm listening,' or 'I'm interested in what you're saying'—just as a way to confirm the social relationship between us," she says. These sorts of emojis seem to be fostering social cohesion.

Negative emojis, on the other hand, affected words and interpretation differently. Recipients in their study read frowns, angry faces, and tears as indicators of a much more specific mental state, and they processed these symbols much more carefully and more in-depth, Pfeiffer says. "It is a lot more revealing from the sender's perspective to send a negative emoji than a positive one." And while positivity serves as a social cement holding us together—even, it appears, in emoji form—negative sentiments require plumbing the depths of a relationship or of a shared understanding to clarify their intent. And just as when we're engaging in-person, they are more likely to spur miscommunication.

Emojis are also filling other social gaps born from our shift to a digital lifestyle. In her work, Linda Kaye, a psychologist at Edge Hill University in Ormskirk, England who is writing a book that synthesizes emoji research, has explored how these ubiquitous icons can reveal valuable clues to a person's personality.

Interactions through social media platforms are often assumed to be opaque—and they do lack many markers that humans rely on to understand and make accurate judgments about each other. Kaye decided to test whether the way people use emojis online might help others get to know what they're like. She and her colleagues asked a group of people with a presence on Facebook (now Meta) to complete a written personality questionnaire, and then they had another group look at screenshots of their profiles.

Looking at five major dimensions of personality, they found that the kinds of emojis people used in their profiles helped viewers assess two of them—open-mindedness and extraversion—with reasonably good accuracy.[6] And while extraversion is pretty easy to judge in person, open-mindedness can be tough to gauge. "That tells us that when we are forming first impressions, actually online sometimes might give us more behavior to help us understand open-mindedness than offline targets," Kaye says.

It turns out that a world freshly speckled with 😃s is not really such a changed world after all. Nor as flat as many might assume. "Ultimately, communication—the purpose of it and the way we do it—inherently doesn't change all that much," Kaye explains. "I would say it's more about expanding our range."

To me, as I continue on my newly emoji-strewn path, that's an inspiring thought because it suggests we don't need to poopoo such novel concoctions but can see them as a triumph of the dazzling adaptability of the human brain. And I will seek delight in the fact that our species can not only access conceptual and emotional language so rich as to craft resonant works of literature like *Moby Dick*—but also can crowd-source a full translation of it into emojis: 🐳.

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REFERENCES

1. Yuasa, M., Saito, K., & Mukawa, N. Emoticons convey emotions without cognition of faces: An fMRI study. Extended Abstracts Proceedings of the 2006 Conference on Human Factors in Computing Systems (2006).

2. Yuasa, M., Saito, K., & Mukawa, N. Brain activity when reading sentences and emoticons: An fMRI study of verbal and nonverbal communication. *Electronics and Communications in Japan* **94**, 17-24 (2011).

3. Churches, O., Nicholls, M., Thiessen, M., Kohler, M., & Keage, H. Emoticons in mind: An event-related potential study. *Social Neuroscience* **9**, 196-202 (2014).

4. Weissman, B. & Tanner, D. A strong wink between verbal and emoji-based irony: How the brain processes ironic emojis during language comprehension. *PLOS One* **13**, e0201727 (2018).

5. Pfeifer, V.A., Armstrong, E.L., & Lai, V.T. Do all facial emojis communicate emotion? The impact of facial emojis on perceived sender emotion and text processing. *Computers in Human Behavior* **126**, 107016 (2022).

6. Wall, H.J., Kaye, L.K., & Malone, S.A. An exploration of psychological factors on emoticon usage and implications for judgment accuracy. *Computers in Human Behavior* **62**, 70-78 (2016).

Will Humans Leave a Trace?

A thought experiment plumbs archaeology and geology to find an answer

BY JOEL FROHLICH

IN THE 1968 FILM *Planet of the Apes*, a crew of human astronauts travels into the future and lands on an alien planet that a civilization of non-human primates inhabits. Only when the film's protagonist discovers a half-buried Statue of Liberty on the shore does he realize that this is not an alien world, but rather a future Earth dominated by a new species of intelligent apes that have taken over after humanity's demise.

The scene is as provocative today as it was 55 years ago. *Homo sapiens*, the futurists tell us, may one day be succeeded by another intelligent species. But how do we know another intelligent species didn't come before us? After all, if civilization had also arisen from an earlier, now-extinct animal species, where are the ruins of its cities? If we found fossils of dinosaurs that lived tens of millions of years ago, we should also have found relics of tombs and temples built in the deep past.

In 2018, climatologist Gavin Schmidt and astrophysicist Adam Frank published an intriguing paper in the *International Journal of Astrobiology* called, "The Silurian hypothesis: Would it be possible to detect an industrial civilization in the geological record?" The title is derived from a *Doctor Who* episode featuring a reptilian race known as the Silurians who gained intelligence before humans. The purpose of the Silurian hypothesis isn't to assert that another civilization came before us. Rather, it's a thought experiment to get us thinking about how we would know if a pre-human civilization once existed, a point that might be too subtle for some netizens in our age of *Ancient Aliens* memes.

Schmidt and Frank acknowledge that paleontologists haven't uncovered fossilized evidence of pre-human civilizations—but that's the point. If a civilization thrived millions of years prior to us, its artifacts could have been destroyed. Geological processes such as tectonic plate subduction and glaciation could easily erase evidence of ancient urbanization.

In a *Planet of the Apes* scenario, archeologists of a post-human civilization—let's call them xenoarcheologists—would find remnants of a metropolis full of skyscrapers like New York City. But likely not if enough time has passed.

Schmidt and Frank write that a "species as short-lived as *Homo sapiens* (so far) might not be represented in the existing fossil record at all." Today, less than 1 percent of the Earth's surface is urbanized, a tiny proportion that hardly stands a chance of being re-exposed millions of years in the future. Unless humans continue to live on Earth for millions of years, our tenure on this planet might be far too brief to leave any trace. "Most of the surface gets completely restructured after a few million years," Frank told me by email. "So there simply is no (almost no) old surface around which might be hiding such structures."

Dinosaurs roamed Earth from about 245 million to 66 million years ago. If archaeologists can discover dinosaur fossils, wouldn't xenoarcheologists discover human fossils? Probably not. At least 1,000 dinosaur species existed on Earth for 180 million years, yet for all the billions of dinosaurs that ever lived, we have only uncovered a few thousand nearly complete fossils. "We estimate that we have one dinosaur fossil for every 10,000 years—which is a tiny fraction of the ones that lived," Schmidt said.

Anatomically modern humans have only existed for 300,000 years—about 0.2 percent as long as dinosaurs—so the prospects of xenoarcheologists finding our fossil remains millions of years in the future are slim to none. Even if a human fossil is discovered in the future, xenoarcheologists would need to find it accompanied by technological artifacts—otherwise, they might think that *Homo sapiens* were just another unremarkable species of ape.

HOWEVER, A FEW CLUES might tell us whether we were here first. In a 2022 paper, Frank, along with the astrobiologists David Grinspoon and Sara Walker, outline several lasting signatures that an intelligent civilization like ours might leave behind. Although we might intuitively feel that a big discovery should come from hitting an archaeological jackpot, such as unearthing a landfill or the Statue of Liberty, the researchers emphasize that the most likely clues would be "global" signatures, spread across our planet.

By the turn of the last century, Frank and his colleagues write, "There were human beings on every landmass and our artifacts, from microscopic plastic debris to released fossil CO_2, stretched from the deep ocean to the upper atmosphere, and even to the moon and other planetary bodies." When fossil fuels are burned, the carbon isotopes get distributed almost uniformly around the globe. A skewed ratio of carbon isotopes would hint to xenoarcheologists that an unnatural process occurred.

"You don't need to be super lucky to find just the right spot where something happened, the signal is being spread by the air, the water, and life itself," Schmidt told me. Similarly, microplastics might form an ocean sediment layer testifying to an extinct civilization's litter. "Sunlight is a good decomposer for plastic—as long as it's in the light!" he said. "However,

TEO TARRAS / SHUTTERSTOCK

DELIBERATELY BURIED A civilization with rocket technology might leave artifacts beyond Earth, like the conspicuous alien monolith that astronauts uncover on the moon in *2001: A Space Odyssey*. To look for evidence of past intelligence on Earth, we might, ironically enough, look to other worlds.

plastic that falls to the deep ocean, or gets incorporated into ocean sediments—dark, slightly acidic, anoxic environments—might have a very different lifetime, conceivably millions of years."

Perhaps it's the swan songs of bygone civilizations that leave marks in the geological record. Burning fossil fuels would not only leave a carbon signature—the resulting climate change should also appear obvious to geologists of the future. Fifty-five million years ago, the Earth warmed abruptly by more than 5 degrees Celsius. At the same time, the ratio of carbon-13 to the most abundant carbon isotope, carbon-12, sharply fell. Was this event, known as the Paleocene–Eocene Thermal Maximum, a natural occurrence brought on by exuberant volcanoes, or the demise of an industrial civilization that overheated the globe?

Although the latter possibility would be the ultimate plot twist in the story of life on Earth, Schmidt and Frank caution that "care must be taken not to postulate such a cause until actually positive evidence is available."

Schmidt admits that his and Frank's thought experiment has been met with a few good counter arguments. "The best one is probably the issue of deep mining," Schmidt said. "We are mining very old deposits for metals and ore, and if these had been depleted by a prior civilization, it might have been noticed. These place limits on the scope of a prior civilization, but don't eliminate the possibility."

A second argument asserts that if a terrestrial civilization before humans achieved technology comparable to our own, we would find it in space. A civilization with rocket technology might leave artifacts beyond Earth, like the conspicuous alien monolith that astronauts uncover on the moon in *2001: A Space Odyssey*. To look for evidence of past intelligence on Earth, we might, ironically enough, look to other worlds.

Since the beginning of the space race, humans have left numerous spacecraft on other planets and moons. Most of these artificial objects lie on our moon, which might be tectonically active but has no atmosphere. Without much of the conventional erosive processes that would chisel away at human artifacts on Earth, the Apollo landing sites will probably remain as monuments to human presence for ages.

Along these lines, a 2012 paper by astrobiologist Jacob Haqq-Misra and planetary scientist Ravi Kumar Kopparapu in the journal *Acta Astronautica* suggested

Geological processes could easily erase evidence of ancient urbanization.

that non-human artifacts on the moon might be identifiable by the emission of microwave or infrared radiation. So, while searching petapixels of visible light data for an odd-looking boulder might be a fool's errand, a thermal camera could speed up the search. "The discovery of an unexpected temperature anomaly on the lunar surface," they wrote, "could be a signature worthy of further investigation."

Similarly, astronomer David Kipping has suggested that we should build a time capsule on the moon as a "tomb of knowledge" testifying to our existence, one that future civilizations may discover. "The moon's going to be there for 5 billion years. That's a long time for somebody to come by and detect, maybe, a strange pattern that we draw on the sand," he told podcast host Lex Fridman earlier this year.

The "consensus seems to be that artifacts on the moon ... have a very long life indeed," Schmidt said. Even so, they may not last forever. In 2011, Mark Robinson, principal investigator of NASA's Lunar Reconnaissance Orbiter mission, said in a news briefing that, "In human terms, it may seem like forever, but in geologic terms, probably there will be no traces of the Apollo exploration in, let's say, 10 to 100 million years." While there is no wind or water erosion on the moon, the naked landscape lies vulnerable to UV radiation, micrometeorites, and occasional macrometeorites that wear away at artifacts.

SCHMIDT AND FRANK'S Silurian thought experiment raises important points that could help solve the Fermi Paradox—the puzzle of why we see no signs of life elsewhere in the universe despite the vast number of other stars and planets. Could today's astronomers already be looking straight at signatures of deep-space aliens and failing to recognize them? "It's all connected," Schmidt told me. In both cases—looking for a pre-human civilization on Earth or alien intelligence in deep space—"we are going to be faced with multivariate signals that could have natural causes, and we are going to have to think about the conclusions in a probabilistic way."

Schmidt himself has thought about one conclusion to a pre-human civilization. At the same time that he and Frank published "The Silurian hypothesis," Schmidt published a short story called "Under the Sun." This work of fiction is based on the thought experiment introduced in Schmidt and Frank's peer-reviewed paper.

Although the Paleocene–Eocene Thermal Maximum is ambiguous, a faster and more violent civilization-ending catastrophe would leave a clearer signature. If a civilization before humans annihilated themselves in a nuclear war, radioactive plutonium left from nuclear fallout would linger for many millions of years. Plutonium cannot be formed by any natural process occurring on Earth. Its most stable isotope, plutonium-244, has a half-life of 80 million years. That's short enough that little-to-no natural sources remain from the primordial building blocks that formed Earth, yet long enough that appreciable amounts could remain for multiple geological epochs following a nuclear conflict.

Schmidt told me that this isotope "could conceivably be a marker of a nearby supernova as well as thermonuclear war," but the supernova possibility could be ruled out if astronomers failed to detect a corresponding nebula left behind by a star that exploded in our stellar neighborhood. In his view, finding unexpected amounts of plutonium-244 in the geological record "would be pretty significant—particularly if there were precursor anomalies in other tracers." If the United States and Russia ever launch full-scale nuclear Armageddon on the world, it will be some small consolation to humanity that, in annihilating ourselves, we plant a plutonium flag of our existence for ages to come.

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Have We Gotten Dark Matter All Wrong?

Physicists have yet to pinpoint the hypothetical matter that keeps galaxies from flying apart. Now they have a new focus.

BY PAUL M. SUTTER

IN THE 1930S, the bolo-tie-wearing astronomer Fritz Zwicky found something strange in the motions of galaxies. They were moving far too quickly within their clusters than they should be, based on their mutual gravitational attraction. The clusters also should have scattered themselves apart billions of years ago, but yet they remained intact. Figuring that there was some component of the clusters at work that he could not directly see, the Swiss scientist named this material "*dunkle Materie*"—dark matter—and moved on.


SAKKMESTERKE / SHUTTERSTOCK

> *We might need to radically revamp our understanding of fundamental physics—and the universe itself.*

Decades later, astronomer Vera Rubin found a similar oddity. In the 1970s, she discovered that stars within galaxies were orbiting much faster than they should be, meaning that there had to be an invisible substance, one that was suffusing every galaxy, keeping everything from flying apart like an out-of-control merry-go-round. It must be something like Zwicky's dark matter.

Today, modern cosmologists have dozens of independent lines of evidence that point to the existence of dark matter, from the behavior of individual galaxies to the evolution of the universe itself. And yet we can only detect its presence through gravity, meaning that we have no idea what dark matter really is—despite estimates that it accounts for more than 85 percent of the mass of every galaxy in the universe.

After nearly a century of hunting, cosmologists are now worried that the search for dark matter is growing cold. Is dark matter a sort of highly technical, scientific version of magical thinking? A tidy way of explaining away gaps in our limited, human understanding? If scientists don't find more concrete evidence for dark matter soon, we might need to radically revamp our understanding of fundamental physics—and with it, the universe itself.

To solve numerous long-standing problems in physics, including dark matter, in the 1980s, some theorists proposed a new kind of particle, known as a WIMP: a weakly interacting massive particle. Despite their name, these particles would be rather hefty, easily outweighing more familiar particles like protons and neutrons. But otherwise, these dark matter particles would share nothing in common with those we know; WIMPs would not participate in the electromagnetic force, rendering them invisible to direct observation (with the small exception of the extremely rare interaction with normal matter through the weak nuclear force).

Cue the ensuing particle (and Nobel) chase, with advanced efforts, like the Cryogenic Dark Matter Search, popping up around the globe, charged with the mission of catching a stray WIMP.

Decades after the initiation of these missions, the grand total of captured or detected WIMPs is … zero.

These results have not been entirely unproductive. Particle physics and cosmology can tell us the gross properties of this mysterious particle (or particles, if there happens to be more than one type comprising the universe's dark matter), but it has not been able to provide the specifics. Null results in these experiments can at least tell us what the dark matter is *not*. And as the years go on, the range of possibilities of what the WIMP *could* be have gotten narrower and narrower.

But now the constraints are so narrow that physicists are wondering if we've gotten dark matter all wrong. Our experiments are tuned to find WIMPs. These WIMPs are heavy particles motivated by theories in particle physics. So perhaps our continued null results are telling us that WIMPs aren't the answer. Maybe it's something else, even more ghostly, even more effervescent, even lighter.

The idea that dark matter is made of a particle that is much, much lighter than we previously thought doesn't

GOING DEEP For decades, scientists have been searching for traces of the dark matter that seem to explain the other-wise unexplainable in our universe. But big experiment, after big experiment (such as the Large Underground Xenon experi-ment, pictured here, which was built 4,850 feet underground at an abandoned mine in South Dakota) have failed to turn up traces of proposed particles known as WIMPs. So cosmologists are expanding their ideas of what dark matter might be.

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come out of nowhere. For one, we already know of one kind of particle that is both lightweight and invisible: the neutrino. We have not yet ascertained the precise mass of the neutrino, but our upper limits place its mass at no higher than about 500,000 times lighter than the electron (the electron itself is about 2,000 times lighter than the proton).

Second, other outstanding problems in high-energy physics have suggested their own classes of new particles, known as axions, that would also happen to fit the bill of ultra-light and otherwise invisible particles. These particles would sail through our detectors without a hint of their existence, potentially explaining why we have yet to find the dark matter that seems so integral to explain our observations of the universe.

Just as in the case of the WIMPs, there is a wide variety of potential masses for this form of ultra-light dark matter. In the most extreme cases, the dark matter particle could be a *trillion-trillion* times lighter than the electron.

And this is where things get strange. The proposed WIMPs are exotic because they are largely invisible but otherwise act like normal particles. They would zoom around through space like tiny little dark bullets, exactly like any other particle of nature would do.

But the ultra-light dark matter is so light that it would look more like, well, light. All objects in nature exhibit wave-particle duality, sometimes manifesting their behaviors as waves and sometimes as particles. Most fundamental particles spend most of their lives acting like particles, bouncing and wiggling at will. But ultra-light particles act more like waves, sloshing and scattering around. The lightest particles we know are the photons, the carriers of the electromagnetic force, and are completely massless, and they are often very wavy: You can squeeze light through narrow channels, bend it around corners, and add the particles together just like waves of water.

Ultra-light dark matter would behave in the same way. Instead of buzzing around like billions of furious invisible bees in the cosmos, this form of dark matter would slosh back and forth, with waves of dark matter lapping against the stellar shores of every galaxy. An ocean of dark matter, with the galaxies as nothing more

than brightly lit buoys bobbing up and down in their gravitational embrace.

This form of dark matter would slosh back and forth, lapping against the stellar shores of every galaxy.

Just as waves of water can converge into tremendous freak tidal waves, researchers have discovered that ultra-light dark matter could theoretically clump up on itself, forming invisible "dark stars" made of concentrated dark matter. If the ultra-light dark matter interacts with itself, these dark stars could become extremely dense, right on the precipice of forming black holes, before ripping themselves apart in a singular burst of energy, completely invisible to any telescope.

But searching for these ultra-light ghost particles requires a far different approach than a quest for WIMPs. Newer experiments, such as the Axion Dark Matter eXperiment at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics, use resonant cavities buried deep underground. The hope is that when an axion encounters an incredibly strong magnetic field, it could occasionally find itself turning into a photon. So, if we design an experiment with an incredibly strong magnetic field and find more photons in the apparatus than we expect, it might be a sign of axions floating around us. If dark stars exploded, these kinds of experiments might see a burst of axions (signaled by a sudden surge of extra photons) flooding through their detectors, just as we see a flash of light when stellar supernovas go off.

Nature is unforgiving. Our best ideas, no matter how motivated by theory, by elegance, or even by sheer will must all stand up to experimental scrutiny. If there's no evidence to support an idea, we must discard it.

The dark matter hypothesis—that there is a substance that dominates the mass of the universe that is largely invisible—can only remain viable if we someday find direct evidence for these new kinds of particles. The nearly 40-year-old WIMP paradigm is becoming increasingly untenable. But it could be that axions and their ultra-light cousins are no more likely to exist.

It could be that we are completely, totally off base. That there is no new particle; that what we know of the universe from our current understanding of particle physics is it. In this scenario, we must still explain our cosmic observations. We could do this by modifying our understanding of the force of gravity. Einstein's general relativity has proven itself in every experimental trial it has faced, but past results are no guarantee of future returns.

Unfortunately, every single attempt to go beyond Einstein's theory to explain away dark matter as a great cosmic misunderstanding has failed in their own way. Today, there are no viable alternatives to general relativity that are able to explain the totality of evidence we have so far in favor of dark matter (in other words, theories that modify general relativity to explain one observation or another, like the motions of stars within galaxies, *still* require at least some "*dunkle Materie*" to explain the remaining observations).

If we fail to find direct evidence for dark matter in any form, whether WIMP or ultra-light, we'll have some serious work to do. *Something* must explain the observations that we are making in the wider universe. Perhaps some brilliant mind will come up with a revolution of our understanding of gravity, wiping away the need for dark matter in a new, all-encompassing paradigm. Perhaps another genius will devise an extension to particle physics and find an entirely new class of particles that can account for the dark matter with properties that we can detect with new methods.

Or, perhaps we will be doomed to decades more of frustration, with all evidence pointing to the existence of dark matter despite our inability to directly detect it, forcing us to revise our understanding of the relationship and role of all forms of matter in the universe.

In the meantime, we can hold out hope for the possibility that we are awash in a vast sea of particles so faint that only in the motions of galaxies can we find evidence for their subtle but essential machinations, unseen dark stars exploding around us.

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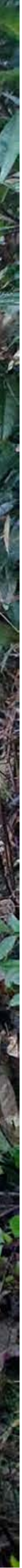
Michael Levin on a hike
in the Kathmandu Valley.



The Biologist Blowing Our Minds

Michael Levin is uncovering the incredible, latent abilities of living things

BY GEORGE MUSSER

MICHAEL LEVIN, A DEVELOPMENTAL BIOLOGIST at Tufts University, has a knack for taking an unassuming organism and showing it's capable of the darnedest things. He and his team once extracted skin cells from a frog embryo and cultivated them on their own. With no other cell types around, they were not "bullied," as he put it, into forming skin tissue. Instead, they reassembled into a new organism of sorts, a "xenobot," a coinage based on the Latin name of the frog species, *Xenopus laevis*. It zipped around like a paramecium in pond water. Sometimes it swept up loose skin cells and piled them until they formed their own xenobot—a type of self-replication. For Levin, it demonstrated how all living things have latent abilities. Having evolved to do one thing, they might do something completely different under the right circumstances.

PHOTO BY GEORGE MUSSER

Slime mold grows differently depending on the music playing.

Not long ago I met Levin at a workshop on science, technology, and Buddhism in Kathmandu. He hates flying but said this event was worth it. Even without the backdrop of the Himalayas, his scientific talk was one of the most captivating I've ever heard. Every slide introduced some bizarre new experiment. Butterflies retain memories from when they were caterpillars, even though their brains turned to mush in the chrysalis. Cut off the head and tail of a planarian, or flatworm, and it can grow two new heads; if you amputate again, the worm will regrow both heads. Levin argues the worm stores the new shape in its body as an electrical pattern. In fact, he thinks electrical signaling is pervasive in nature; it is not limited to neurons. Recently, Levin and colleagues found that some diseases might be cured by retraining the gene and protein networks as one might train a neural network. But when I sat down to talk to the audacious biologist on the hotel patio, I mostly wanted to hear about slime mold.

How did you come to cut up slime mold?

I was doing a home-school unit with my oldest son, and we wanted to understand what the slime mold *Physarum* does. It's growing in a Petri dish of agar. It behaves by changing its shape. It crawls this way or that way. Also, it's unicellular; the whole thing is one cell. No matter how big it is—it could be meters across—it's one cell.

You've got a little treat, which is an oat flake, and it starts to grow toward the oat flake. Then you can take a razor blade and cut off the leading edge. After, you have two individuals: You have the big one, and you get the small one. Now, the small one has a choice to make. It can go get the food first, or it can go rejoin the rest of the *Physarum* and then go get the food. If it gets the food, it doesn't have to share the food with this giant mass behind it. The nutrient density of that reward is huge.

With any kind of behaving organism, there is a calculus of payoff: If I do this, I win this much, and if I do that, I win that much. You have to make decisions. It's always a trade-off of what are you going to do. People study this with game theory and things like the Prisoner's Dilemma. You and I are competing and potentially cooperating over some resources. The number of players is constant. But the *Physarum* scenario is a kind of Prisoner's Dilemma game where the number of players isn't constant. Not only can you cooperate or defect, but you could also split and merge. How do you think about making decisions when the borders of your self are not fixed?

So what happened?
It preferred to first rejoin the rest.

The smaller individual that's been created by the razor cut is faced with the choice, "I can take this food and keep it to myself" or "I cease to exist." Why would there be any alternative for that creature? Why would it want to reassimilate into the collective?
Because existing as a separate individual may not be the highest payoff. Once you rejoin the rest of the group, you lose the ability to be an independent individual, but what you gain is greater stability as part of a whole, because you're less likely to dry out, for example.

Are the cells of our body continually measuring the payoff of cooperating vs. defecting, too?
Yes, but if you are a cell that's connected strongly to its neighbors, you are not able to have these kinds of computations. "Well, what if I go off on my own? I could just leave this tissue. I could go somewhere else where life is better. I could set up my own little tumor." You can't have those thoughts because you are so tightly wired into the rest of the network. You can't say, "Well, I'm going to ...." There is no I; there's we. You can only have those thoughts, "What am I going to get?" when you're not part of the group.

But as soon as there's carcinogen exposure or maybe an oncogene that gets expressed, the electrical connection starts to weaken. It's a feedback loop, because the more you have those thoughts, the more you're like, "Well, maybe let me just turn that connection down a little bit. Now I'm really coming into my own. Now I'm out of here. I'm metastasizing."

So a carcinogen would work in this case by disrupting the bioelectrical connections.
Exactly. What we've done in the frog system, and we're now moving into human cells, is to show that [electrical weakening] happens, and that you can prevent it and prevent normalized tumors by artificially forcing the electrical connection. We can shoot up a frog with strong human oncogenes and then show that, even though those are blazingly strongly expressed, there's no tumor because you've intervened. You've forced the cells to be in electrical communication despite what the oncogene is trying to get it to do.

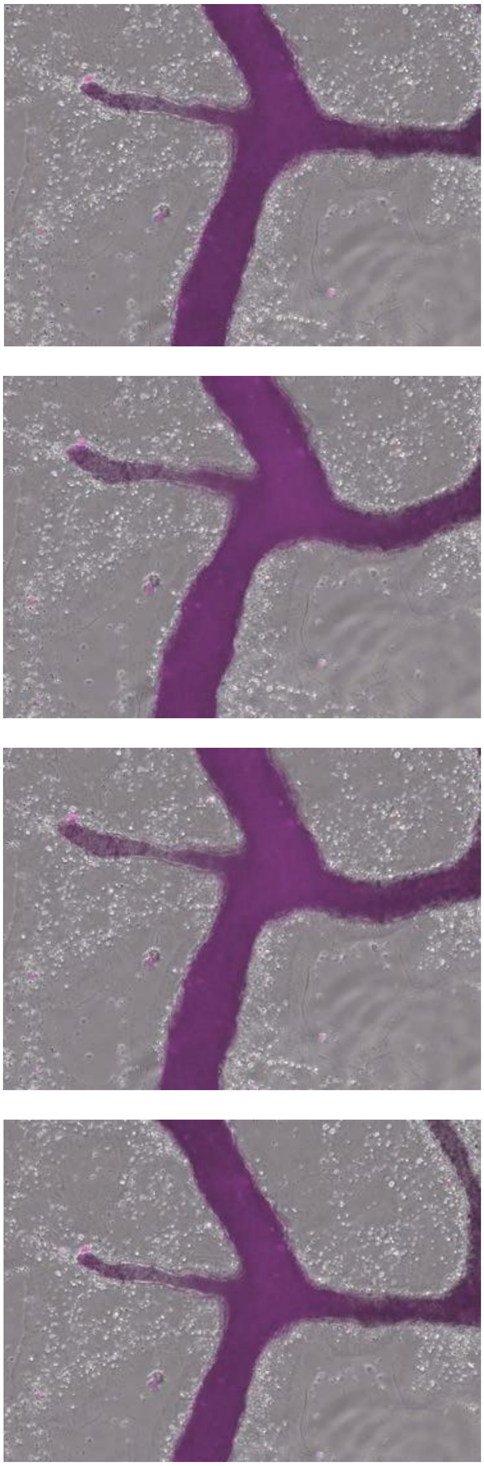
Said one cell to another, "I'm out of here. I'm metastasizing."

One slide you skipped over in your talk was, "Why don't robots get cancer?" I'm intrigued!
The reason cancer is not a problem in today's robotics is because we build with dumb parts. The robot may or may not be intelligent to some degree, but at the next level down, all the parts are passive; they don't have any goals of their own. So, there's never a chance that they're going to defect. Your keyboard's never going to wander off and try to have its own life as a keyboard. Whereas in biology, it's a multi-scale architecture where every level has goals, and there's pros and cons to this. The pros are you get these amazing things we're talking about now. The con is that sometimes you get defections as a failure mode, and you get cancer.

To go back to the slime mold, how does it decide?
We know it has memory. It can learn from experience. We know it does make all kinds of decisions if you give it various options of things it can do. The whole thing is a hydraulic computer. We injected little fluorescent beads into the thing. There are flows through the cytoplasm. And the cool thing is that if you have a fork like a "Y," you see that it just shuts one branch off, and the stream only goes the other way. It has selective control over each branch point—it's a synapse, basically.

Almost like a little transistor.
Exactly right. Once you have that, you can make logic gates, and you can make anything. Now you can do computations.

Another thing is it has these vibrations. It's constantly tugging on the surface. We have this wild paper where we put one glass disc here, three glass discs back here. There's no chemicals, there's no food, no gradients. It will cogitate for about four hours, just kind of sitting here doing nothing. And then boom!—it grows out toward the three.



SLIME MIND These time-lapse photos of *Physarum polycephalum*, a slime mold with one cell and no brain, shows the mold is able to move by shifting protoplasm within it, and through its vibrations, sense surrounding objects.

NIROSHA MURUGAN, LEVIN LAB

What it's doing is sensing strain in the medium. It's pulling, and it feels the vibrations that come back. It's ridiculously sensitive because each disc is like 10 milligrams. For whatever bizarre reason, it prefers the heavier mass. During those four hours it collects the data, decides where it's going, and then, boom!

If it's sensitive to vibrations, does it react to music?
We grew the *Physarum* on a plate, and the plate was sitting on a speaker, and my student was driving the speaker with her iPhone. And we could see that for certain types of music, it would grow quite differently than for others.

What music in particular?
The thing is, she was 19 years old, so I didn't recognize any of the artists that she was telling me about. But that's a real easy home science project. Somebody could totally do that with their kids. Some of them, it grew very nicely. Some of them, it just didn't grow at all. It just really hated it; it just hunkered down.

What else have you discovered about *Physarum* psychology?
If you place a small piece of food nearby and then a much larger piece of food far away, it tends to go for the larger piece and bypasses the small one, which I thought was really weird, because why wouldn't you grab it along the way? But it just sort of fixated on the big one and went for that. Maybe it thought it would come back later for the smaller.

Because it's so slow and small, it can't catch its prey; it grows probably a centimeter every couple hours. My postdoc and I had this idea: What if it has a way of slowing other things down to its level? She put some planaria [flatworms] on there, and she saw that the planaria basically stopped moving; they got anesthetized. They slowed down to the point where the *Physarum* could eat it. So we made an extract out of it and put it on frog embryos, and the frog embryos slowed down their development. They didn't stop; they just really slowed down. So it probably is a real slowdown as opposed to some kind of anesthetic.

So many things can suffer that have nothing to do with a human brain.

A big theme of your work has been that organisms have latent abilities—that the behavior we see in nature is contextual and that, by altering the circumstances, you coax them to do totally different things. What are some examples?

We are lulled into thinking that frog eggs always make frogs, and acorns always make oak trees. But the reality is that once you start messing around with their bioelectrical software, we can make tadpoles that look like other species of frogs. We can make planaria that look like other species of flatworms across 150 million years of evolutionary distance—no genetic change needed, same exact hardware. The same hardware can have multiple different software modes.

You can look at frog skin cells and say, "All they know how to do is how to be this protective layer around the outside. What else would they know how to do?" But it turns out that if you just remove the other cells that are forcing them to do that, you find out what they really want to do—which is to make a xenobot and have this really exciting life zipping around and doing kinematic self-replication. They have all these capacities that you don't normally see. There's so much there that we haven't even begun to scratch the surface of.

Some object to speaking of what the cells "know" or "want" to do. Do you think that a concern about being anthropomorphic or anthropocentric has hindered research in this?

Incredibly so. I love to make up the words for this stuff because I think they need to exist—"teleophobia." People go screaming when you say, "Well, it *wants* to do this." People are very binary because they're still carrying this pre-scientific holdover. Back in before-science times, you could be smart like humans and angels, or you could be dumb like everything else. That was fair enough for our first pass in 1700, but now we can do better. You don't need to be at either of these endpoints. You could be somewhere in the middle. When I say this thing "wants to do XYZ," I'm not saying it can write poetry about its dreams. It doesn't necessarily have that kind of second-order metacognition; it doesn't know what it wants. But it still wants.

Do you think there are agents, maybe we've encountered them already, that we're not recognizing or couldn't recognize as such?

All over the place. We're made of them. Charles Abramson and I wrote this primer for figuring out how intelligent any system is. Could it habituate? Could it be sensitized? Can it do associative learning? Can it do fear conditioning? I'm sure once we start looking, we're going to find degrees of agency all over the place.

Given that we could conceive of, say, AI systems or tornadoes as agents, how should we respond? Does our response have ethical implications?

I absolutely think it has massive ethical implications. Anybody who doesn't read a lot of sci-fi is so behind on this. There are so many things out there that can suffer that have nothing to do with a human brain. I do think that you could formulate something like the new Golden Rule: "Be nice to goal-seeking systems in some sort of proportion to their capacity to do it." I don't think we want to get to the point where we are afraid to roll bowling balls down an inclined plane because we don't want to hurt their feelings. People who worry about various kinds of AI today, never mind tomorrow's, aren't crazy at all. Humanity has a long history of moral lapses toward creatures that don't look enough like them.

GEORGE MUSSER is an award-winning science writer and the author of the forthcoming book *Putting Ourselves Back in the Equation*, as well as *Spooky Action at a Distance* and *The Complete Idiot's Guide to String Theory*. Follow him at @gmusser@mastodon.social and @gmusser.bsky.social.

5 Amazing New Discoveries About Light

Invisible cloaks. Ghost imaging. Scientists are manipulating light in ways that were once only science fiction.

BY SIDNEY PERKOWITZ

YOU MIGHT THINK that after centuries of studying light, we know pretty much everything about it. It's true we've had breakthrough after breakthrough in using it, from illumination to communication, from examining the micro- and macro-universes to scanning our own bodies. We understand that light is an electromagnetic wave, thanks to James Clerk Maxwell, whose equations established that in 1865; and that it also appears as quantum packets of electromagnetic energy called photons, as Albert Einstein recognized in 1905. But the more we look into light, the more we see and the more we learn. The classical view of light as a wave still produces new science as light waves interact with artificial "metamaterials"; and we are still exploring light as a quantum particle. Both approaches provide ways to manipulate light that were once only science fiction. Here are five recent marvels.

VLUE / SHUTTERSTOCK

1. BENDING LIGHT FOR INVISIBILITY

The magical invisibility rings and cloaks featured in fantasy stories reflect the ancient human dream of hiding things and people from sight. Invisibility shows up in science fiction too, like *Star Trek*, where hostile Romulan spacecraft conceal themselves with a cloaking device. This uses an idea from relativity, that strongly distorted spacetime makes light curve around the spacecraft as if it didn't exist.

Physicists don't yet know how to do that, but the classical optics of light waves and light rays points to another solution. We see an object as it interacts with incoming light. In principle, an invisibility cloak could intercept those incoming rays and bend or refract them into itself so they travel inside the cloak and emerge along their original paths. An observer, seeing what looks like undisturbed light, would think nothing is there, just as flowing water smoothly splitting around a rock and then recombining gives no downstream indication of the rock. But to make light follow this complex path, the cloak needs to be made from a metamaterial.

Researchers first tested this idea in 2006 with a rigid metamaterial cloak, a hollow cylinder whose wall held thousands of small structures that made microwaves traverse suitable paths within the wall. Placed around an opaque metal object, the cloak made the object nearly completely vanish under microwave radiation. Since then, researchers have made small inanimate

INVISIBILITY CLOAK

We see an object as it interacts with incoming light. In principle, an invisibility cloak could intercept those incoming rays and the observer, seeing what looks like undisturbed light, would think nothing is there.

EHAY HAY / WIKIMEDIA COMMONS

objects and a fish, a cat, and a hand vanish under ordinary visible light, but only as seen over a narrow angle of view. Others have developed a flexible cloak that wraps around a small object to make it vanish, but only at one wavelength. Science can't yet make a cloak that completely hides a person in ordinary light; but invisibility research is thriving and we're approaching Harry Potter's wondrous cloak.

We're approaching Harry Potter's wondrous cloak.

2. LIGHT PUSHES AND PULLS THINGS

Like thrown rocks, photons carry momentum that they transfer to an object on impact. This radiation pressure is why sunlight pushes comet tails away from the sun, and why it can propel a spacecraft. In 2010, the Japan Aerospace Exploration Agency (JAXA) launched IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun, honoring Icarus who flew near the sun in myth). Its thin, tennis court-sized polymer sail gathered solar photons, which collectively exerted a small force that steadily accelerated IKAROS. Six months and 300 million miles later, it arrived on target near Venus without using any fuel for propulsion. Now JAXA and other space agencies are considering longer missions using bigger, more effective solar sails.

Remarkably, a light source can also pull an object toward itself, against the direction that the light propagates. Physicists have shown that within a specially shaped laser beam, the forward push of photons on a particle is dominated by a backward force due to the particle's own electromagnetic response. The effect is strong enough to pull a microscopic object like a biological cell backward toward the laser. In 2023, however, a related experiment showed that a low-power laser could pull a comparatively big macroscopic object, 0.2 inch x 0.1 inch. This is hardly a powerful sci-fi "tractor beam" that can reel in an entire spacecraft, but it could provide a new way to remotely sample the atmosphere on Earth and other planets, and phenomena like comet's tails.

3. GHOST IMAGING: PICTURES IN THE DARK

Suppose you want to form an image of something like a living cell that could be changed or harmed by the light energy that illuminates it. Ghost imaging uses the phenomenon of photon entanglement to produce an excellent image of a barely illuminated object. Entangled photon pairs, which are formed by certain optical processes, are quantum-correlated, such that measuring the properties of one immediately reveals the properties of the other, no matter how distant.

In ghost imaging, one of each of a swarm of entangled photon pairs interacts with the object and encounters a detector that simply registers its arrival. A second beam of the corresponding entangled partners

Light was slowed to 38 mph, which a fit cyclist could match.

never touches the object but goes straight to a sensitive multi-pixel detector. Computer analysis of the correlations between the two detector results creates a high-quality image of the object, even with weak illumination. This approach has uses such as converting images covertly taken by invisible infrared light to visible images detected by a high-resolution camera; or obtaining good quality X-ray images from a patient exposed to a low, relatively safe X-ray dose.

4. QUANTUM SLITS IN TIME

In the famous double-slit experiment, first done in 1801, a light beam splits as it passes through two narrow slits in an opaque barrier. On the far side, the beams spread and overlap to form a pattern of bright and dark areas on a screen, showing that light consists of waves that can interfere with each other. But a modern version of the experiment where just one photon at a time is aimed at the slits still produces a wave-like interference pattern. According to Richard Feynman, this striking, still unexplained example of wave-particle duality "has in it the heart of quantum mechanics … it contains the only mystery."

Now physicists have reproduced this experiment with slits in time rather than space. They used a thin film of indium tin oxide (ITO), which is transparent to infrared light but quickly becomes reflective within 10-15 seconds when excited by a laser. In the experiment, the researchers shot infrared light at the ITO. When the ITO became a mirror for a short time, the reflected infrared light remained in its original form. But when the ITO mirror was very briefly turned on and off twice in rapid succession, the reflected infrared light showed definitively that it had interfered with itself as a result of passing through not one but two time portals or slits.

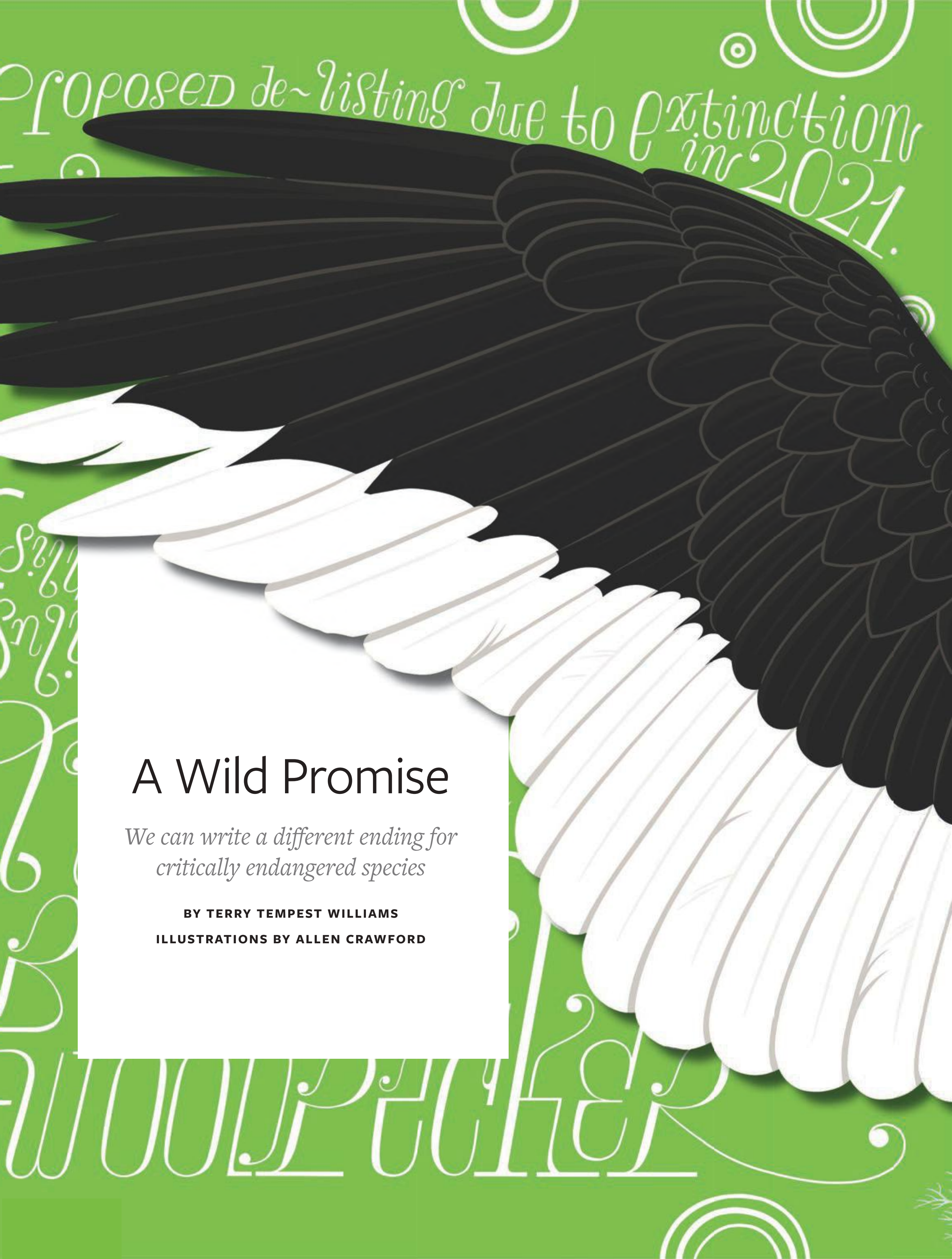
One observer has commented that this work could become a classic like the original double-slit experiment. By extending that into time rather than space, the research offers a new way to explore "the only mystery." The work also shows the feasibility of using metamaterials like ITO to control light in optical systems and quantum computers at ultrafast speeds.

5. OVERTAKING LIGHT ON A BICYCLE

If there is one physics fact that people know, it's that light is the fastest thing in the universe, traveling at 186,000 miles/second in a vacuum. The speed is reduced somewhat when light interacts with ordinary matter, dropping, for instance, to 124,000 miles/second in optical fiber and plain glass. This is still fast enough to circle the Earth in a fraction of a second; and so it was big news in 1999 when Harvard researcher Lene Hau enormously slowed light to the human-scale speed of 38 miles per hour, which a fit cyclist could match. This was accomplished in an exotic medium, a dense gas of sodium atoms cooled to nearly absolute zero. The result was a quantum medium called a Bose-Einstein condensate. Light interacts with this more strongly than with any ordinary medium and so it was hugely slowed. Later, Hau topped this achievement by bringing light to a screeching halt, then later recovering it and sending it on its way.

These results are breakthroughs in fundamental physics and could be useful as well, except for the need to work at temperatures near absolute zero. But since the original work, other researchers have slowed light in gases and solids at room temperature, making it possible to use slowed and stopped light in practical devices. These are currently being developed, for example, to synchronize signals in fiber optic networks and to store digital data in computers. Both applications are important steps toward developing advanced telecommunications networks and quantum computers based entirely on light rather than conventional electronic chips.

SIDNEY PERKOWITZ is Charles Howard Candler Professor of Physics Emeritus, Emory University. His latest books are *A Short Introduction to Physics* and *Science Sketches: the Universe from Different Angles*.



A Wild Promise

We can write a different ending for critically endangered species

BY TERRY TEMPEST WILLIAMS

ILLUSTRATIONS BY ALLEN CRAWFORD


Status under review:
Recent evidence
suggests its possible survival.

ON THE 50TH ANNIVERSARY of the Endangered Species Act, I am thinking about extinction and what that means for a creature, a living being, to vanish from existence. Say their names: great auk, passenger pigeon, Carolina parakeet, Steller's sea cow, Caribbean monk seal, Great Plains wolf, Puerto Rican long-nosed bat, Maryland darter, Utah lake sculpin, Labrador duck, heath hen, Bachman's warbler, Xerces blue butterfly, Wyoming toad, and Panamanian golden frog—all extinct beginning in the 1800s to present.

Imagine an individual animal or insect or plant—alone—reaching, wandering, wondering, if they are the last of the living members of their kind. Certainly, they must know, sense, or fear this fact. What must it be like to surrender to one's isolation by way of howl or cry or flight or bloom to attract a response, a glimmer or glint of kin?

The Sixth Extinction is upon us. It is true, species extinction has been a natural part of the Earth's evolutionary history, as evidenced with the disappearance of dinosaurs in the Cretaceous Era, 65 million years ago, to the extinctions of the great megafauna such as mammoths and mastodons in the late Pleistocene Era who inhabited the last ice age some 10,000 years ago. But scientists today report an accelerated loss of biodiversity 1,000 times faster than the natural rate of approximately one to five species annually.

Now on the brink of extinction in North America are the red wolf, wood bison, grizzly bear, black-footed ferret, California condor, ocelot, Florida manatee, northern fur seal, loggerhead turtle, green sea turtle, giant sea bass, Oregon spotted frog, O'ahu tree snail, rusty-patched bumblebee, Hine's emerald dragonfly, Kirtland warbler, Eskimo curlew, wood stork, willow flycatcher, North Atlantic right whale, beluga whale, and elkhorn coral.

Loneliness inhabits my body as I whisper the names of the extinct and endangered, something better to do in a circle as ceremony, as we pay our respects and contemplate their lives together. How are we to survive without our companion species on Planet Earth? We are not above them or below them—but side by side—fellow creatures caught in a web of uncertainty in this era of the Anthropocene where our human footprint lands heavy on the Earth.

Grief is part of extinction that when understood and witnessed becomes an emotion that parallels love. When the last Rabbs' fringe-limbed tree frog died in the care of the Atlanta Botanical Gardens on Sept. 26, 2016, I wept. I had visited the Atlanta Botanical Gardens that year and knew the single remaining member of this species, tenderly named "Toughie," was holding on—his call penetrated the walls of the Gardens—but there was never a call back in response. He was an Endling.

Today, over 1,400 species appear on the Endangered Species list under the jurisdiction of the United States Fish & Wildlife Service, all part of the Endangered Species Act signed into law on Dec. 28, 1973, by President Richard M. Nixon.

President Nixon wrote, "This legislation provides the Federal Government with the needed authority to protect an irreplaceable part of our natural heritage—threatened wildlife." Just before putting his pen to paper to seal this landmark act, he said, "Nothing is more priceless and more worthy of preservation than the rich array of animal life with which our country has been blessed."

The Endangered Species Act was introduced in the U.S. House of Representatives and the Senate by Congressman John Dingle and Senator Mark Hatfield. It passed the House in an overwhelming majority with only four opposing votes. The Senate vote was unanimous. Hard to imagine in this current period of political divisions; harder still to imagine this act of compassion for all living beings remains intact despite previous polarizing times. It is a testament to the moral vision adopted by Congress with a collective commitment to the continuing health of vulnerable species and securing a livable future of all generations—winged, hoofed, scaled, and rooted.

Fifty years since its inception, there has been a gradual erosion of the Act. In 1978, when a three-inch perch known as the snail darter was listed as an endangered species, it collided mightily with the Tennessee Valley Authority's construction of the Tellico Dam. The Endangered Species Act halted the project. This was more than David taking on Goliath. This was a tiny fish swimming in the way of a monstrous water project. The spotted owl in the forests of the Pacific Northwest was threatened by wholesale clearcuts during the 1990s, igniting the timber wars between loggers and environmentalists. Lines were drawn. Violence threatened environmental activists choosing to live in the upper canopies of redwood trees as a protest. Trees were spiked to teach anyone with a chainsaw a lesson: "Hands off old-growth forests." Any sort of amiable agreement was at loggerheads. Thankfully, solid legal ground was held for both the spotted owl and snail darter, and their endangered status was upheld by science and the courts. In time, solutions were sought through arduous negotiations discussing issues and process. Common ground was eventually found, and in some cases, even consensus.

During the terms of presidents Ronald Reagan and George Herbert Bush, amendments were made to the Endangered Species Act including the formation of a "God Squad" comprised of federal arbiters appointed to balance the common good of capitalism with the survival of a species. It, too, was not without its controversy and contentions. In the American West, where states like Nevada and Utah have a higher percentage of public lands (owned by the federal government) than private lands, a "sagebrush rebellion" ensued, still alive as witnessed by the Bundy standoff at the Malheur National Wildlife Refuge in 2014. The fight over the rights of private landowners and the rights of the federal government to oversee and protect threatened species continues. The battle between ecology and economy persists, but the Endangered Species Act of 1973 endures.

How do we place a monetary value on what one wild life is worth—let alone the value of a species' right to continue when weighed against the perfection of adaptive evolution over time? Do we gauge it through dollars per board feet, or the millennial standing of a redwood forest? Do we approve one more golf course in the desert, or act on behalf of a community of threatened Utah prairie dogs in times of drought? How do we balance the health of a declining grizzly bear population against the wealth of private landowners in a state like Montana and with a desire for a second or third home in Paradise Valley? Respect, restraint, and accommodating the rights of other species continue to butt up against the individual dreams and desires of humans.

Grief is part of extinction that when understood parallels love.

The International Union of Concern for Nature (IUCN) has a "red data book" that is the gold standard for the "global extinction risk status of animal, fungus, and plant species." It is known as the IUCN Red List of Threatened Species, established in 1964 and updated continuously. We know, through shared science from governments around the world, that biodiversity is on the decline. In 2022, the IUCN has registered more than 142,500 species on the Red List, with more than 40,000 species threatened with extinction: 41 percent of amphibians, 37 percent of sharks and rays, 34 percent of conifers, 33 percent of reef-building corals, 26 percent of mammals, and 13 percent of birds. The breakdown is sobering.

Why should we care? We care because we have co-evolved with the living world of animals and plants and fungi and corals and multitudes of microorganisms, many that have never been seen or defined or categorized or named. "The great majority of species of organisms—possibly in excess of 90 percent—remain unknown to science," the venerated scientist E.O. Wilson wrote before his death in 2022. He also coined a word, biophilia, to mean "the inborn affinity human beings have for other forms of life, an affiliation evoked, according to circumstance, by pleasure, or a sense of

Today, over 1,400 species appear on the Endangered Species list.

security, or awe, or even fascination blended by revulsion." We care because it is in our deepest nature to live and learn and evolve from the life that surrounds us.

We imitate animals through dance and song and stories. In ceremonies, their skins are donned; in fashion, we wear their prints and feathers; in art, we draw them, paint them, and sculpt them, making masks to honor them; and in every religious tradition animals from snakes to lions to locusts and doves we reference them, we fear them, we worship them and bow. They are our teachers, our mentors and guides capable of portending our future because they were here to meet us when we arrived. "Men are born human. What they must learn is to be animal," says ecologist Paul Shepard. "If they learn otherwise it may kill them, and kill life on the planet."

IF THE ENDANGERED SPECIES ACT itself has been protected for the past five decades by the passionate research of scientists and the savvy of committed lawyers with the flexed muscle of grassroots organizations, I believe what is being called forth in the 21st century is the strength of our collective will—fierce and direct. As David Lamfrom, vice president

GREEN SEA TURTLE (*Chelonia mydas*) Found in the waters along the Atlantic, Pacific, and Gulf coasts of the U.S. Human activity like boat traffic, commercial fishing gear, shoreline habitat destruction, plastics, chemical pollution, and poaching are major causes of population decline.

of regional programs at the National Parks Conservation Association, says, "Our opening position now must be 'No more.' " No more compromises on the survival of grizzly bears, wolves, and wolverines. No more "taking" (a euphemism for killing) of prairie dogs and development in the critical habitat of black-footed ferrets and burrowing owls. No more draining of precious wetlands where scores of threatened species are making their last stands. No more apathy on our part. No more wondering what we can do when the Endangered Species Act needs heart-fires of support when Congress will inevitably move again to threaten the Act's beautiful, shimmering teeth of accountability in the name of justice for all.

"Right now, in the amazing moment that to us counts as the present, we are deciding, without quite meaning to, which evolutionary pathways will remain open and which will forever be closed," writes Elizabeth Kolbert in *The Sixth Extinction*. "No other creature has ever managed this and it will, unfortunately, be our most enduring legacy."

The illustrations here are by Allen Crawford. He has created an illustrated celebration of the Endangered Species Act, vibrant and instructive by featuring 80 vulnerable species. He is a visionary artist who not only cares about the survival and sustaining grace of the "more-than-human world" but has chosen to put his gifts to use with the intention of inspiring us to care more deeply and act more consciously on behalf of these vulnerable creatures.

Some of the creatures are critically endangered. Some are threatened. Perhaps as you

come to know their stories, you will be moved to seek out an endangered or threatened species that lives close to you, learn their natural history and give them not only your attention, but your devotion. Or maybe you know of a species in your state or a particular ecosystem that needs federal protection. You can support a specific species campaign addressed to the U.S. Fish & Wildlife Service to nominate newly threatened plants and animals to be considered for protection under the Endangered Species list. Advocates in the Northern Rockies are working to upgrade the status of the wolverine from a "species of concern" to "threatened." The Endangered Species Act is an act of love that asks for our engagement, each in our own way with the gifts that are ours in the places we call home. Learn their names. Speak their names. Remember their names. Act.

As a child, I watched the men I loved in my family lift their high-powered rifles and shoot one prairie dog after another and another for fun, and then walk away. They called them "pop-guts." On the way back to our camp, I stepped over their small blood-soaked, blown-apart bodies left in the matted grasses of their prairie dog town. And then, a single prairie dog raised her head out of a burrow and stood up and faced me. I froze in place, unable to avoid her gaze. She disappeared underground. On that day, I made a vow, short of standing in front of my father's rifle, that I would be their ally. I have tried to keep that vow.

How do we place a monetary value on what one wild life is worth?

I graduated from high school in 1973, the same year the Endangered Species Act was signed into law. At that time only 3,300 Utah prairie dogs remained in 37 isolated colonies in the state of Utah. Due to political pressure from ranchers and developers, they were not listed on the original Endangered Species list. Prairie dogs were seen as vermin.

In 1977, I lobbied the Utah legislature as a graduate student in education from the

RED WOLF (*Canis rufus*) Once found throughout the southeastern U.S. Causes of its near-extinction in the wild include shooting, poisoning, roadside fatalities, habitat destruction, and interbreeding with coyotes. The killing of red wolves reintroduced to federal and state lands in North Carolina has thwarted recovery efforts.

University of Utah. I had created a Utah prairie dog curriculum for the Salt Lake City school district. At the State Capitol, I was met with incredulity and disdain by representatives who insisted on calling prairie dogs "varmints." The Speaker of the House handed me a recipe for "Prairie Dog Stew." Finally, in 1984, the Utah prairie dog was added to the Fish & Wildlife's Endangered Species list and remains on the IUCN Red List of Threatened Species.

In 2000, in a special millennial issue of *The New York Times Magazine*, the Utah prairie dog was featured as one of 10 species most likely to become extinct by the next millennium. Their fate was to become a ghost species. I wrote a book on prairie dogs. Every month I sent a picture of prairie dogs in different poses (one with a helmet and bazooka) to friends at The Utah Nature Conservancy, a playful nudge for protection. Did any of these gestures make a difference? It made a difference to me. This was my wild promise that became a vow I made to the lone Utah prairie dog who survived my family's massacre.

What is the difference between a promise and a vow? A promise is "a specific declaration or assurance that one will do a particular thing or that a particular thing will happen." A vow is "a solemn promise"—a deepening gesture that one makes with one's whole being. Both are nouns. But what if we see them as verbs, as actions that grow out of a commitment?

A promise becomes giving one's word—"assuring someone that one will definitely do, give, or arrange something; undertake or declare that something will happen." A vow is an open-ended commitment over time that moves into the realm of a sacred obligation—"dedicated to someone or something, especially a deity." If one believes, as I do, that the Divine resides in all living things, then there are many gods among us, in a myriad of shapes and sizes and forms.

> Perhaps you have often felt yourself watched.
> Perhaps you were right.
>
> —Helen Mort, *The Illustrated Woman*

WHETHER IT IS A WOLF lodged deep inside our psyches or a mite invisible to our eyes, each species encompasses a life honed to perfection over millions of generations. Our wild promise within the Endangered Species Act, to protect and keep safe threatened and critically endangered species from extinction, can become a vow

Oceangoing form of
Rainbow
Trout
Native Range:
tributaries and
coastal waters
of the North Pacific.
causes of population
decline along U.S.
West coast include
habitat loss due to
dams, pollution,
concrete channels,
groundwater pumping,
heat island effects,
and other byproducts
of urbanization

STEELHEAD TROUT (*Oncorhynchus mykiss*) Oceangoing form of rainbow trout found in the tributaries and coastal waters of the North Pacific. Causes of population decline along the U.S. West Coast include habitat loss due to dams, pollution, concrete channels, groundwater pumping, heat island effects, and other byproducts of urbanization.

of action. What I have learned from spending time in Utah prairie dog towns is that community matters. These communal animals watch out for each other. Each member of a colony has a carefully communicated role to play.

Could they be watching out for us, as well? By caring for their own kind, prairie dogs simultaneously create an environment where other species can thrive. They are a keystone species that other species rely on for their survival. Where prairie dogs dwell other species dwell, also—including black widow spiders, pronghorn antelope, burrowing owls, badgers, meadowlarks, and rattlesnakes. Each species fulfills their ecological niche. Diversity equals stability. Prairie dogs continue to teach me, we are nothing without community in all its magnificent and infinite variety.

Do we approve one more golf course in the desert?

We, too, are threatened. Endangered species are showing us now that we are not immune from the perils of climate collapse. The issues affecting endangered species, such as habitat destruction from extreme weather, to drought, to fires, are inextricably linked. My friend Becky Duet and her family, who are Cajun, have lived in the bayous of Louisiana for generations. They lost their home in the summer of 2021 to Hurricane Ida. The eye of the hurricane split in two, something

HINE'S EMERALD DRAGONFLY (*Somatochlora hineana*) The only dragonfly included in the Endangered Species Act. Found in spring-fed marshes, sedge meadows, and alkaline fens over calcareous rock formations in Illinois, Michigan, Missouri, and Wisconsin.

they had never seen. There was no momentary calm—what came instead were 190 miles per hour winds that threatened their lives and blew apart their town of Galliano. Her husband Earl, a renowned shrimper in the area, lost his way a decade ago as the grasslands and waterways he once knew by heart disappeared to erosion. Now the maze of shrimping in the bayous has been lost to open waters. Louisiana loses one football field of soil every hour. The Duet family now belongs to tens of thousands of climate refugees who see what is happening and are sounding the alarm, but not enough of us are listening, watching, and bearing witness to a world transformed.

Our ignorance and arrogance are threatening life on the planet as we continue to live as though nothing has changed, as though our reliance on fossil fuels has no consequences, as if holding fast to our beliefs that we have the right to drill for more and more oil at greater and greater cost to the Earth and its inhabitants will make it right.

This is not a homily, this is a fact: Our relentless drive to protect our American lifestyle while we continue devouring the sacred sites of endangered species for our own short-lived additions is our pathology. This will be our undoing. Respect and restraint will be our healing. Our unconscious and conscious acts of killing must be transformed into intentional acts of reverential vigilance. Animals are leaving us. Plants and fungi are offering us their medicines so that we might see more clearly with greater understanding, our place in the wholeness of things. Native bees continue to pollinate wildflowers and grace us with honey even as their populations plummet. On hands and knees, we would do well to take the humble stance of an animal and remember who we are, where we belong, and what our responsibilities to those with whom we share this planet must become and why.

I often return to these lines from the prose poem "Dead Seal near McClure's Beach" written by Robert Bly—the poem that made me care. His words about a seal dying from spilled oil held a mirror up to my own complicity in the suffering of animals:

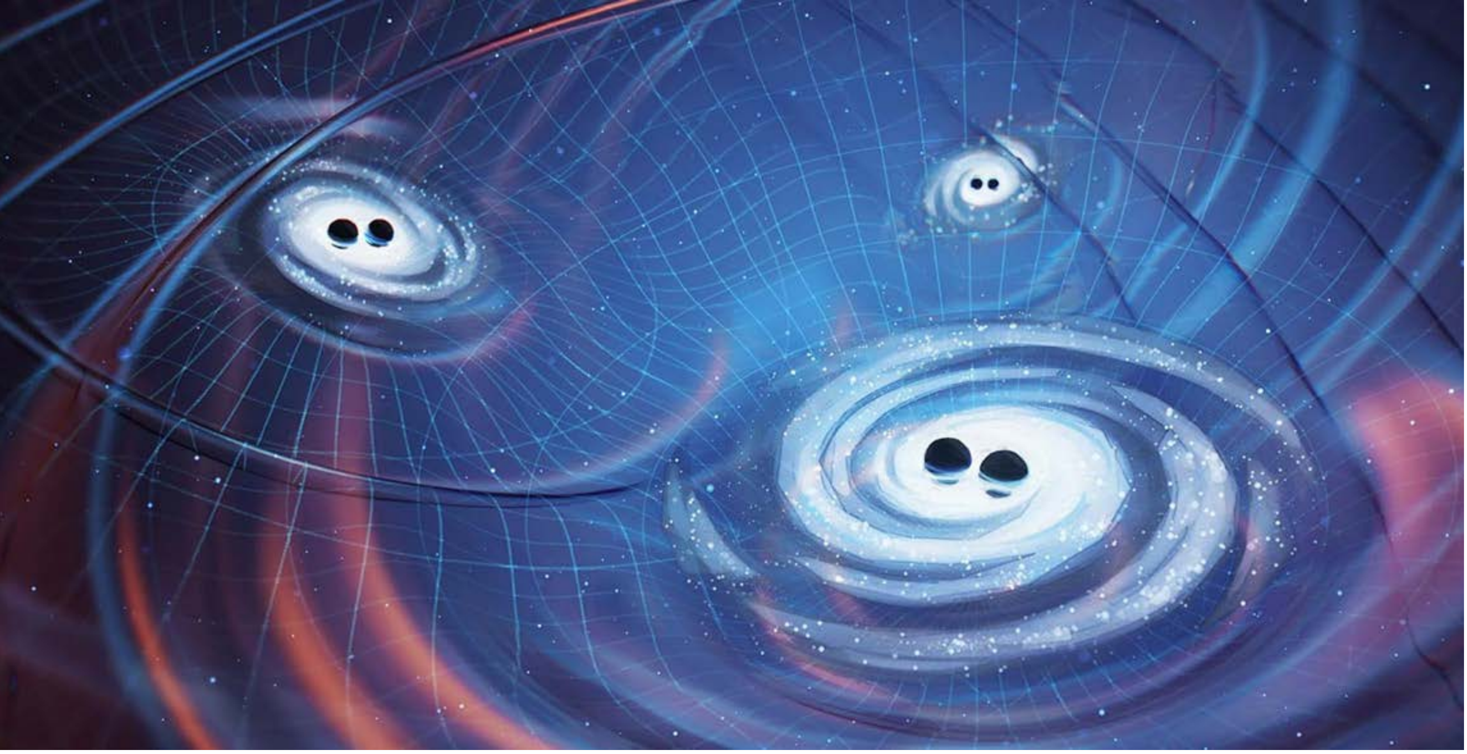
> … goodbye brother, die in the sound of waves, forgive us if we have killed you, long live your race, your inner-tube race, so uncomfortable on land, so comfortable in the ocean. Be comfortable in death then, when the sand will be out of your nostrils, and you can swim in long loops through the pure death, ducking under as assassinations break above you. You don't want to be touched by me. I climb the cliff and go home the other way.

WE CAN WRITE a different ending to the stories of critically endangered species and all the miraculous creatures large and small whose populations are in decline. Their lives are in our hands. A new ending is possible once we begin to love and live differently.

TERRY TEMPEST WILLIAMS is an American writer, educator, and conservationist. Her award-winning books include *Refuge*, *When Women Were Birds*, *The Hour of Land*, and *Erosion: Essays of Undoing*. She lives in Castle Valley, Utah.

ALLEN CRAWFORD is the illustrator of *Whitman Illuminated: Song of Myself*. He and his wife, Susan, are proprietors of the design and illustration studio Plankton Art Co. Their illustrations are on permanent display at the American Museum of Natural History's Milstein Hall of Ocean Life. His work has appeared in numerous publications including *The New York Times*, *Orion*, and *Art in America*. He lives in Mt. Holly, New Jersey.


IUCN global population estimate: over 30,000 individuals
Listed as
in
Range: Remnant Habitats in Illinois, Michigan, Missouri, and Wisconsin.



A Supermassive Test for Einstein's Famous Theory

How a gravitational wave background re-opens the book on general relativity

BY MELIZE FERRUS & CHIARA MINGARELLI

Y**OU'RE OSCILLATING.** Well, technically, not just you. We are all being stretched and squeezed by an event we can't see—at least not with the naked eye. Imagine that throughout the day we have imperceivable fluctuations in our height, starting taller in the day, shorter at night, constantly stretching and squeezing like a spring. Our entire universe experiences something of the same, just rather than fluctuations repeating every 24 hours or so, it's every decade.

OLENA SHMAHALO FOR NANOGRAV

Somewhere, far, far away and long, long ago, two supermassive black holes came together, forming a binary system. These black holes have gargantuan masses, at least 100 million times the mass of our sun. They were bound to each other in a seemingly perpetual orbital dance, spending tens of millions of years orbiting each other, creating ripples in the fabric of spacetime that may soon be detectable to us. As the two continue their tango, they lose energy and draw their counterparts in closer and closer. These eonic spirals are dances that we, the authors, spend our brain cycles chasing.

As we get closer to discovering them, we're uncovering secrets that could revolutionize the knowledge of the physics governing the most massive black holes known to humanity, the evolution of galaxies, and if the universe on large scales works the way Einstein said it does.

Energy lost by black holes when they merge was first predicted by Einstein in 1916, though he believed that the ripples these black holes make—these gravitational waves—would be too small to ever detect. His theory, general relativity, explains gravity is caused by a massive object curving space and time around it, unified by a new quantity called spacetime. Using the principles dictated by this theory, the concept of gravitational waves was born.

Gravitational waves—ripples in the fabric of spacetime itself—can be created when accelerating masses, such as pairs of black holes, begin to merge. As these gravitational waves plow through the universe, they stretch and squeeze all the fabric of spacetime itself, causing everything to oscillate like a pair of swing dancers as they pass through, onto their next partner.

The prediction of gravitational waves emitted from merging black holes took 100 years to validate. Indeed, it took decades of technological advances to create an instrument sensitive enough to make the first gravitational wave detection, back in 2015. That instrument, called LIGO, can only detect gravitational waves from black holes about 10 times the mass of the sun, called stellar mass black holes. To detect supermassive black holes, we need to build an astronomically larger gravitational wave detector.

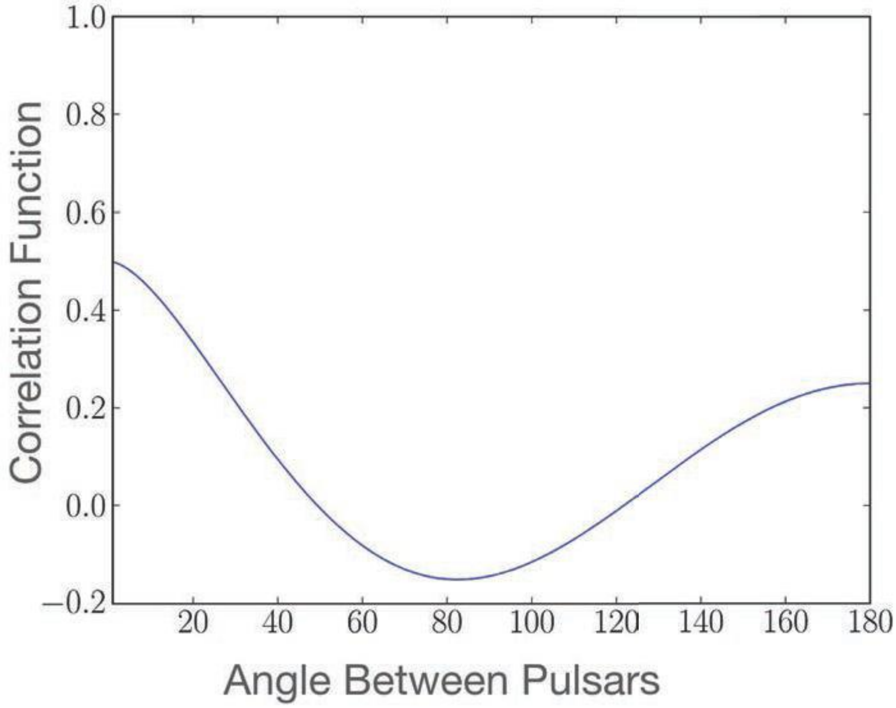
Looking back at the slowly orbiting supermassive black holes, gravitational waves are emitted in all directions like an ever-enlarging pirouette. This whirling can be seemingly perpetual: Each orbit lasts years to decades, and the whole merger process can last millions of years, maybe longer. There's a supermassive black hole at the center of our own Milky Way galaxy, called Sagittarius A*, weighing in at a whopping 4 million solar masses.

Pulsar pulses are so exact and predictable that they are nature's original gravitational wave detector.

Even more interestingly, this isn't happening with just one supermassive black hole binary. Potentially millions of supermassive black holes are slowly orbiting their partner, with each of their gravitational wave signals stacking up on top of each other to create gravitational noise—or a gravitational wave background. This background has an amplitude which is set by the number of supermassive black hole binaries which create it, their distance from the Earth, and the masses of the black holes themselves. This amplitude also varies as a function of gravitational-wave frequency, from the nanohertz regime to the microhertz regime—millions of times lower frequency than the LIGO detectors can ever measure. But how can we detect such low-frequency gravitational waves? Concretely, a billion solar mass supermassive black hole binary at a frequency of 1 nanohertz takes about 30 years to complete an orbit.

How do these merger signatures manifest in the gravitational wave background? For example, stars and gas are much better at driving black holes to merge when they are widely separated. It's not until the black holes are very close that gravitational wave emission really takes over. We can predict that the amplitude of the gravitational wave background might be lower than expected at very low frequencies, where the gas and stars are doing most of the work in pushing the black holes together.

Furthermore, these gravitational waves should change the distances between objects by one part in a million billion. To detect such small spacetime



NATURAL CURVE
The distinctive shape shown in the Heiling and Downs chart (left) can't be created by any other natural process. It's considered to be the smoking gun for the presence of a gravitational wave background.

perturbations, we turn to the best natural clocks in our galaxy—millisecond pulsars. These pulsars are neutron stars which emit radio waves that can be detected by radio telescopes on Earth each time they spin around. They can also give us insight into this cosmic gravitational interpretative dance. The arrival times of pulsar pulses are so exact and predictable that they can be timed down to hundreds of nanoseconds over a decade—or one part in a million billion—making them nature's original gravitational wave detector.

As the gravitational waves travel through our galaxy, stretching and squashing the fabric of spacetime, the pulsar pulses arrive a little bit early and a little bit late since the pulsars get a little bit closer, and then farther away. Since we know exactly when the pulsar pulses should arrive, changes to this can signal the presence of gravitational waves. This collection of pulsars and radio telescopes used to time the pulsars is called a pulsar timing array, and it effectively turns the entire galaxy into a gravitational wave detector.

It's been astounding to learn that the universe can gift us ultra-precise data from millisecond pulsars. This is especially mind-blowing, given how hard it was to build the ground-based gravitational wave detectors like LIGO. The level of sensitivity required to detect fluctuations with LIGO took over 40 years to achieve and billions of dollars; meanwhile ultra-stable millisecond pulsars—discovered in 1982—are naturally occurring gravitational-wave detectors. Sapiens, sometimes, have nothing on nature.

Of course, life doesn't stop for anyone, not even a neutron star. There are still internal processes in the pulsar that could potentially contribute to the changes in the period. How does one account for this signal?

By cross-correlating the pulsar arrival times, we can search for a common signal in all the pulsars and beat down any intrinsic pulsar noise. The more pulsars we add to our array, the better our signal gets. After carrying this cross-correlation in the pulsar arrival times, two signals should survive since they are common to all the

CHIARA MINGARELLI

Millions of supermassive black holes may be orbiting their partner, creating a gravitational wave background.

pulsars: the amplitude of the gravitational wave background and the distinctive Hellings and Downs curve.

A fundamental paper written in 1983 by R.W. Hellings and G.S. Downs introduced the idea that cross-correlated pulsar pairs will respond distinctively to the presence of a gravitational wave background. When we have a large number of pulsars, as we do in the North American Nanohertz Observatory for Gravitational Waves, the point-by-point correlation function appears to form a curve. This is called the Hellings and Downs curve. It shows how the amplitude of the gravitational wave background is modified as a function of the angle separating each pulsar pair. This distinctive shape can't be created by any other natural process and is largely considered to be the smoking gun for the presence of a gravitational wave background in a pulsar timing array.

By finding both the presence of the Hellings and Downs curve in our cross-correlated pulsar data, together with a common amplitude signal of the gravitational wave background, we can bring our millions of dancing supermassive black hole pairs to the fore.

As pulsar timing arrays become more and more sensitive, they will be able to measure how the amplitude of the gravitational wave background evolves as a function of frequency, which can give us clues as to what is creating the gravitational wave background. While it is widely held that supermassive black holes should generate this low-frequency background, other sources of low-frequency gravitational waves include primordial gravitational waves from inflation, the quantum fluctuations from a fraction of a second after the Big Bang, and exotic networks of cosmic strings, the theoretical, super dense filaments of matter-energy, which can be the size of the entire universe.

Probing this background will give us deeper insights into open problems in astrophysics. The secrets that are hidden within pulsar timing array data may lead to answering critical questions for astronomers. We will be able to say, for example, what will happen to our supermassive black hole, Sagittarius A*, when our galaxy collides with neighboring Andromeda.

We will also be able to say general relativity has, or has not, passed another test when huge gravitational forces are in play. Indeed, some theories predict that gravity, in very strong gravitational regimes—such as in supermassive black hole mergers—behaves differently than what Einstein suggested. According to general relativity, a supermassive black hole binary's orbit should shrink in a specific way while emitting gravitational waves. Deviations from this could indicate new physics beyond general relativity. Gravitational waves, like light, are also polarized. General relativity predicts two polarizations (called plus and cross), but others could also exist, again pointing to either extensions of general relativity or entirely new physics.

Hopefully, within our lifetime, astronomers will gain insights into these and more open questions, all due to a whole lot of shimmies taking place throughout the universe.

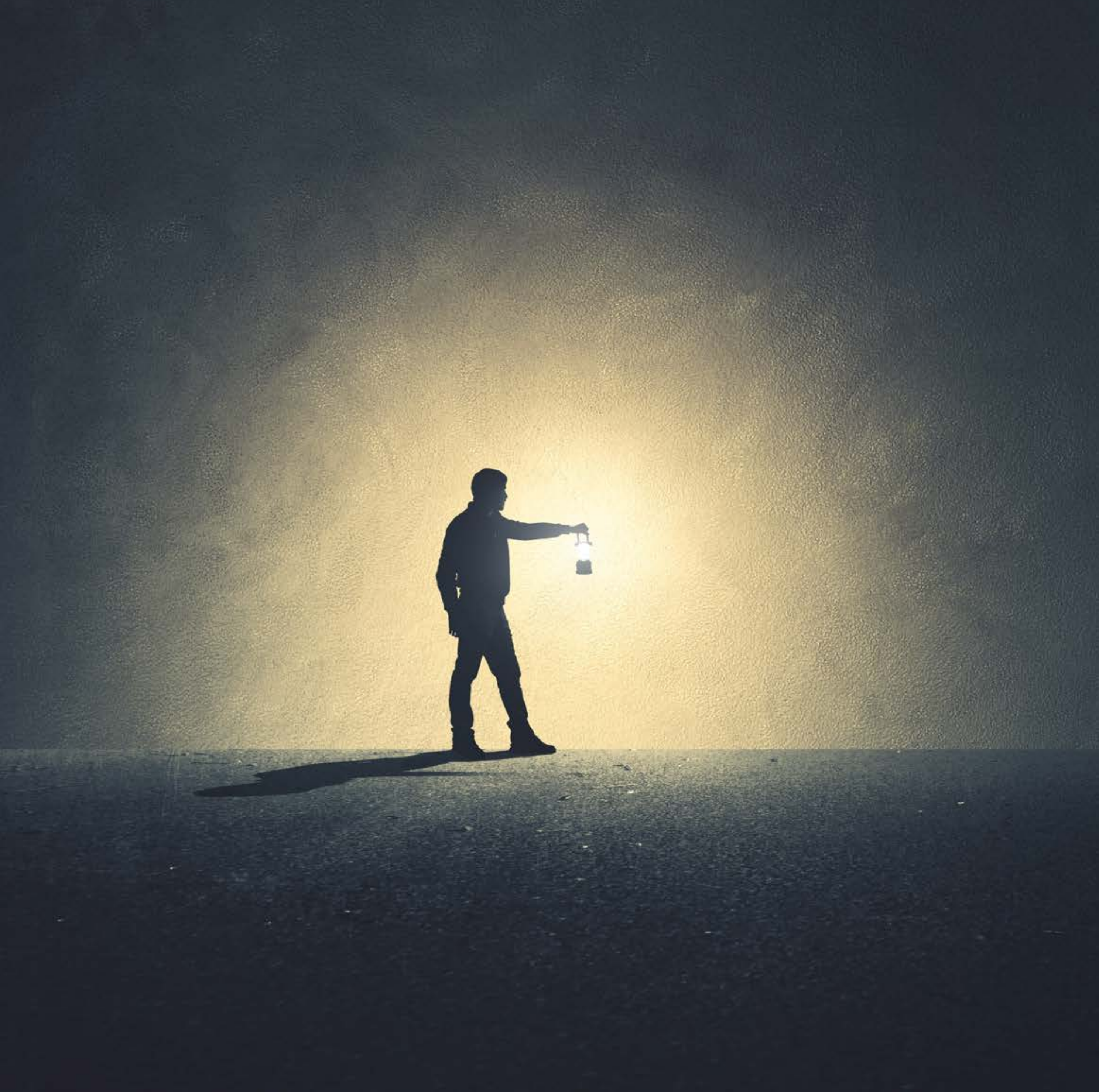
MELIZE FERRUS has been doing research on smaller black hole mergers with the Flatiron Institute's Center for Computational Astrophysics.

CHIARA MINGARELLI is an assistant professor of physics at Yale University and has been thinking about supermassive black hole mergers for over a decade.

Blindness Is a Strange Country

What I'm finding as I lose my sight

BY ANDREW LELAND



I'M GOING BLIND as I write this. It feels less dramatic than it sounds. The words aren't disappearing as I type. I'm sitting comfortably in the sunroom. The sun is rising like it's supposed to. I can plainly see Lily sitting next to me, reading in her striped pajamas. The visible world is disappearing, but it's not in a hurry. It feels at once catastrophic and commonplace—like reading an article about civilization's imminent collapse from the climate crisis, then setting the article down and going for a pleasant bike ride through a mild spring morning.

There's no cure for retinitis pigmentosa (RP), the condition I was diagnosed with more than 20 years ago, so I usually see my eye specialist every other year. During my last visit, she showed me an illustration of how much vision I had left.

It reminded me of ice cubes melting in hot water: two small, wobbly ovals in the center, and two skinny shapes floating along the sides. The wobbly ovals represented the central vision I still had, and the strips were my peripheral vision. I had about 6 percent of what a fully sighted person sees. My doctor frowned graciously as she gestured at the skinny French-fry shapes. "When those go," she said in her medical deadpan, neither cheerful nor grim, "your mobility will become more limited. Those two strips of residual peripheral vision are what you're using to get around."

Describing what I can't see is surprisingly difficult, mostly because my brain adapts to it so quickly. I have severe tunnel vision, but what I see doesn't look like a tunnel; the walls of the enclosure aren't visible.

I have the strongest sense of the contours of my blindness in periods when my vision changes—when suddenly there are things I don't see that I ought to, that I saw until recently. I bump into furniture in my house that hasn't moved in years. I'll put a cup down for a moment and it disappears. I'll painstakingly rake the wobbly ovals and slender French fries of my residual vision across the table's surface again and again, and when I finally find the cup, it's standing blamelessly in what even a few weeks ago I would have described as "plain sight." It's still in plain sight—it's just that my sight is growing less and less plain.

THERE ARE AS MANY WAYS of being blind as there are of being tall, or sick, or hot. But the popular view has always conceived of blindness as a totality. The blind bards wandering the countrysides of ancient Japan, China, or Europe, the blind housed in asylums in the Middle Ages, all the pupils in all the schools for the blind from the Enlightenment onward, blind beggars and lawyers, war veterans and toddlers—in the eyes of history, as well as those of most of their contemporaries, they all saw nothing. Modern dictionaries still subscribe to this sense: Blindness is the antonym of vision, and connotes a destitution of sight.

What else could it mean?

Despite the poetic impulse to equate blindness with darkness, it's rarely experienced as a black veil draped over the world. Only around 15 percent of blind people have no light perception whatsoever. Most see something, even if it isn't very useful, by sighted standards: a blurry view of their periphery, with nothing in the middle, or the inverse—the world seen through a buttonhole.

LEADING ASSUMPTIONS Like Pieter Bruegel the Elder's 1568 painting *The Blind Leading the Blind* (pictured here), cultural depictions of blindness have been overwhelmingly negative, as though everyone who is not fully sighted spends their lives in this muddy, cold pit.

WEB GALLERY OF ART / WIKIMEDIA COMMONS

For some, scenes come through in a dim haze; for others, light produces a shower of excruciatingly bright needles. Even those with no light perception at all have little use for the popular image of blindness as darkness: The brain cut off from visual stimulus can still produce washes of brilliant color and shape. One blind man, whose optic nerve—the connection between the eyes and the brain—had been severed, described seeing a continuously swirling (and distracting) "visual tinnitus." The Argentine writer Jorge Luis Borges, decades into his blindness, still saw color, which sometimes disturbed him: "I, who was accustomed to sleeping in total darkness," he said,

> was bothered for a long time at having to sleep in this world of mist, in the greenish or bluish mist, vaguely luminous, which is the world of the blind. I wanted to lie down in darkness.

The arrival or encroachment of blindness gives rise to a similarly dazzling range of experiences, an efflorescence of blind varietals. There are those born blind, with no visual memories, whose brains—including the visual cortices—develop using four (or fewer) senses to construct their view of the world. Those who become blind in early childhood often retain visual memories that can contribute to an intuitive understanding of visual concepts. The late-blinded may have the most cognitive work to do, forced to relearn basic skills like orientation and information-gathering through new senses, long after their brains' developmental plasticity has hardened. Some late-blinded adults consciously struggle to preserve their storehouses of mental images, like art conservators touching up old and fading masterpieces.

Ancient Greek had one word for totally blind people, *tuphlos*, and a different one, *ambluôpia*, for "dull-sightedness." Ancient writers shared our modern predilection for using blindness as a metaphor for heedlessness and various other moral, intellectual, or spiritual failings. The Greeks and Romans spoke of blind ignorance, blind leadership, and the blindness of wealth and love; the Old Testament described bribery blinding its recipient, and the blindness of those who don't heed the voice of the Lord—those who "have eyes but are blind" (Isaiah 43:8).

Bruegel's 1568 painting *The Blind Leading the Blind* makes literal (and adds several participants to) the

biblical proverb "If a blind man leads a blind man, both will fall into a pit." The painting shows six blind men in a line across the canvas, each holding the shoulder or stick of the man in front of him. The blind guy at the back of the line looks like he's doing all right. As the eye travels across the composition, though, the aspect of disaster gradually increases: The faces contort with growing confusion and distress as the men grimace and stumble, until we see the final blind man, arms and legs thrown wide, falling backward into the proverbial pit. The rest of the men are about to fall in on top of him.

Most disability histories describe the plight of blind people in these terms—as though they spent their lives in this muddy, cold pit. "Want and suffering were the rule rather than the exception and the blind were an economic liability," Richard S. French observed in his representative study, *From Homer to Helen Keller*. "Toleration alone makes such abysmal beggary possible, and rarely does the blind man rise above it." A tour through the Western canon offers a highlight reel of blind abjection: the pathetic stumbling of the cyclops Polyphemus, his eye pierced by Odysseus with timber that had been sharpened and then heated to a glowing red point; Oedipus taking long pins from his mother's garment and plunging them into his eyes ("The bloody pupils / Bedewed his beard. The gore oozed not in drops, / But poured in a black shower, a hail of blood"); the third-century B.C. biblical story of Tobit, who goes blind after a swallow shits in his eyes, believes his wife has become a criminal to support him, and prays for death.

IT WASN'T UNTIL I'D RETURNED HOME after my freshman year in college that my mom decided I'd been complaining about my eyes long enough that I should get them checked out by a specialist. She got me an appointment at an eye clinic at UCLA, where I submitted to a long regimen of tests, including an ERG, which involves numbing your eyes and then attaching electrodes to your eyeballs to measure the amount of electricity your retinas are putting out in response to light. (It's like testing the charge on a battery, but the battery is part of your face.)

Only around 15 percent of blind people have no light perception whatsoever.

When I finally met with the doctor, a soft mustachioed man named Dr. Heckenlively, he confirmed what I'd gleaned from Wikipedia's great-uncle years earlier: I had "classic RP."

I could probably expect to maintain good vision during the day through my 20s and 30s. The night blindness would gradually become more severe, and my peripheral vision would erode. As I approached middle age, the degeneration would sharply accelerate. There is no treatment, he told me, but science is making great progress, so by the time I was *really* blind, in 20 or 30 years, there would hopefully be a cure. In the meantime, there were some vitamins I could take to try to prolong my useful vision. Did I smoke? Yes, of course I smoked. I also had a radio show on the college station called *A Thousand Frowzy Steams*. Well, the doctor told me, I'd need to quit immediately—cigarettes are terrible for ocular health. Can you see stars? he asked.

This was something I'd already noticed: Starlight had become too dim for me to register. It was also the detail that brought it all home for my mom. She sat up straight: "You can't see stars!"

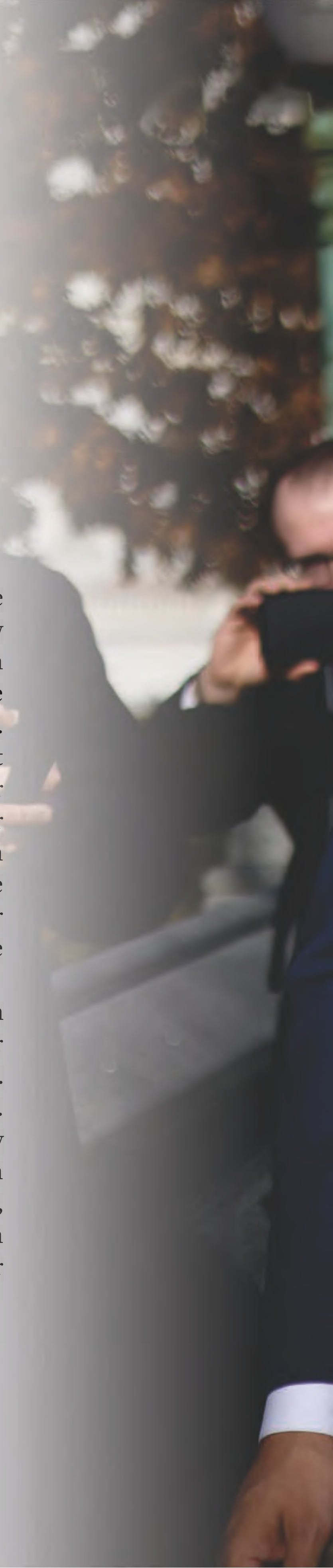
Afterward, we visited a museum downtown, where we saw a show of Richard Serra's *Torqued Ellipses*—huge steel sheets rolled into standing curves set within one another, creating open tunnels. Wandering through these brief mazes, each with only two or three turns to make inside, made it feel like the shape of the whole world had changed; the world itself became a torqued ellipse, with only a strip of the outside splashing in. I felt at once claustrophobic and expansive.

ANDREW LELAND is a writer, audio producer, editor, and teacher whose work has appeared in *The New Yorker*, *The New York Times Magazine*, *McSweeney's Quarterly*, and others. He is an editor at *The Believer* and hosted and produced the podcast The Organist; *The Country of the Blind* is his first book.

The George Santos Syndrome

Why people believe their own lies

BY CLAYTON DALTON



IN DECEMBER 2022, *The New York Times* reported that George Santos, the newly elected Republican Congressman from New York, wasn't who he said he was. Santos presented himself as an experienced financial professional and entrepreneur, with a degree from New York University and stints at CitiBank and Goldman Sachs. He suggested that his mother's death was related to 9/11. He implied that his grandparents were Jewish and survived the Holocaust. But neither NYU, nor Goldman, nor CitiBank had any record of him. His mother was in Brazil in 2001. His grandparents were, by all accounts, Brazilian Catholics. Santos has since admitted to "embellishing his resume" but he continues to maintain that he has Jewish heritage, and that his mother was in the World Trade Center on 9/11. "I stay convinced that that's the truth," he has said.

Lying and deception are perennials of politics. Machiavelli argued in the 16th century that sometimes a leader must act as a "great pretender and dissembler." It's easy to see such politicians as fundamentally cynical. They seem to lie in a Machiavellian attempt to win power and control. Often, no doubt, that's true. But cognitive science suggests the possibility of something more disconcerting at play: You really can believe your own lies. Insight into the nature of memory, based on experimental work, suggests that your awareness of the truth can bend over time. Lies can feel like the truth and so, to you, they are the truth. You're no longer deceiving others. Instead, your brain is deceiving you.

You're no longer deceiving others. Your brain is deceiving you.

In the 1970s, the psychologist Elizabeth Loftus began a series of experiments that upended the conventional view of memory. Previously memory was thought to function like a tape recorder. Information was permanently stored in the brain and retrieved at will. Loftus had a hunch that this wasn't how memory worked at all. She suspected that memory might be far more malleable, and more subject to revision and distortion, than anyone suspected.

In one of her earliest studies, Loftus and her collaborators showed participants a slide sequence of a vehicle accident involving a stop sign.[1] Afterward, some participants were asked about a yield sign, even though there had been no yield sign. Then, on a subsequent memory test, participants were asked whether they had seen a stop sign or a yield sign. In the control group, which hadn't been asked the misleading question about a yield sign, 75 percent correctly remembered the stop sign. In the other group, only 41 percent did. The others wrongly remembered a yield sign. The interviewers had influenced, or even altered, the participants' actual memories. Loftus corroborated this effect in dozens of studies, and later showed that she could implant memories of entirely fictional events in people's minds.[2]

In the 1990s, researchers began asking a different question. Loftus had shown that false information supplied by others could alter memory of an event. What if the misinformation came from yourself?

Psychologists Maria Zaragoza and Jennifer Ackil designed one of the first experiments to test this possibility.[3] They showed a movie clip of two brothers and their adventures at a summer camp to nearly 300 participants, who ranged in age from first grade to college. They divided the participants into two groups and asked them questions about events that had occurred in the clip, as well as about events that had not, which the psychologists made up. The first group was told they didn't have to answer questions about the fabricated events if they didn't want to; most didn't. The second group was told they must answer all the questions, which pressured them to make up details about the fake events. A week later, all the participants were tested on which details had occurred in the video and which hadn't. The first group passed the test handily. The second group, which had been forced to invent things about events they never witnessed, misremembered their fabrications as real, the psychologists explained.

In the early 2000s, two other researchers published studies on the effects of lying on memory. Kerri True, a psychology professor, showed a group of undergraduates a video of a staged robbery.[4] Part of the group was instructed to fabricate a description of the robber. One week later, all the students were asked to answer questions about what they had seen in the video. True found that fabrication corroded memory in two distinct ways. "Those who lied about the description of this character later forgot more of the [actual] details about the character," True told me. Those students were also more likely to misremember their fabricated details as having appeared in the video. It was as though lying cemented the false details in their memory, at the expense of the real ones.

Danielle Polage, a psychologist and former student of Elizabeth Loftus, conducted a test that tried to measure the effect of lying in order to deceive, rather than simply making something up. She recruited a group of students, who completed a questionnaire ranking the probability that they had experienced certain life events as children, like whether they had ever been hospitalized, or lost in a mall.[5] Two weeks later, the students

PAGES 84-85: WIN MCNAMEE / GETTY IMAGES

NORTHALLERTONMAN / SHUTTERSTOCK

were given a list of seven life events they indicated *had* happened to them, and one event that had not. They were instructed to tell convincing, detailed stories to an interviewer about all the events, including the one they hadn't experienced.

A week later, the students were asked to fill out the questionnaire again. For most of the students, lying about an event strengthened their memory that such an event had never occurred. But for a sizable minority, lying about the event led them to indicate that the event had definitely happened to them. Polage had essentially planted an entirely false recollection in their memories without saying a word. She published two more studies, in 2012[6] and 2017,[7] on the effect of deliberate lying on memory, and again found that lying about a childhood event that hadn't happened could lead to the development of a false memory of the event.

In 2008, Zaragoza and cognitive psychologist Quin Chrobak asked another group of undergraduates to watch the video clip of two brothers at a summer camp.[8] This time, some participants were told to fabricate a fictitious event that had not occurred in the video. After one week, participants were given a yes-no questionnaire testing their memory of which events had appeared in the video, and eight weeks later they were asked to provide a summary of the video. At one week, some of the fabricators had already begun to believe that their made-up events had really happened. At eight weeks, when the students were asked to describe the video, the fabricators incorporated the events they had invented into their descriptions more than 60 percent of the time. Even

A BAD TURN In the past six years, says cognitive psychologist Quin Chrobak, who researches distortion in memory, Americans' divorce from facts and truth has led to a burst of interest among psychologists in "how to correct false beliefs." Evidence is mounting, but solutions won't be easy.

the students who identified their fabricated events as imaginary at one week made this mistake after eight weeks. Strikingly, their lie felt truer as time passed.

In the beginning, the participants clearly knew they had made up an event. "But when you test their memory later, you can get error rates over 50 percent," Chrobak told me.

Lying cements the false details at the expense of the real ones.

ALTHOUGH THESE STUDIES used different methods, they all found a remarkably consistent effect of fabrication and lying on memory. A leading explanation has to do with how the brain categorizes memory. In 1993, three psychologists published a paradigm for understanding how the brain keeps track of a memory's origin.[9] They argued that, in fact, it doesn't keep track at all.

"People do not typically directly retrieve an abstract tag or label that specifies a memory's source," the authors wrote. Instead, the brain unconsciously assesses a memory for clues to decide whether the memory was internally generated—such as a lie—or externally generated, as with an actual experience. And among the latter, whether information originated from a trustworthy source or not, or from one person rather than another. In short, our brains consider the overall texture of a memory, through unconscious processes, in determining its likely source and validity. These unconscious processes, the authors argued, ultimately influence our development and expression of knowledge and belief, and color our engagement with the world.

What clues does the brain use to make these unconscious judgments? "When you're trying to figure out a source for a memory," Polage said, referring to unconscious processes in the brain, "you look at a few things. First, perceptual. 'Can I actually hear someone's voice speaking to me?' Then, context. 'I should remember where it was. I should remember who was there.' And then there's emotion. 'I remember walking in and I was the only one who wasn't dressed up; I remember *feeling* really awkward.' " If a memory contains such richness, then the brain is more likely to determine that it corresponds to a real event.

Polage was personifying processes that transpire beneath the veneer of consciousness. What enters awareness, ultimately, is the subsequent *sense* of where a memory came from. If our brains simply tagged every memory with a label specifying its origin, and filed them together, then memory might be less prone to error. But that seems not to be the case. Because we are largely unaware of these cognitive processes, they can be susceptible to mistakes—especially if we happen to embellish a lie with the sort of characteristics that the brain uses to parse what's real from what isn't. We can corrupt these circuits without any recognition that we have done so.

If you tell a lie, the source-monitoring framework should identify the lie as a lie when you remember it later. That's not a conscious process; we're not choosing to remember or neglect that something we said wasn't true. We simply remember the lie as a lie, most of the time, because of the texture and shape of the memory as assessed by subterranean levels of cognition. A lie likely has less perceptual and contextual detail, because you invented it rather than experienced it. Your brain notices that. The associated cognitive processes are different too, since creating a lie has been shown to be more demanding than telling the truth. Your brain also notices that. Your experience of this process is just the experience of correctly remembering that when you told your mother in high school that you spent the night at John's house instead of Suzy's, you were lying.

But we can corrode this process by telling a lie in a certain way. "When you're fabricating lots of details, you're going to be more likely to see source errors," True explained to me, and "the more plausible the detail, the more likely you are to get confused about the source of it." In other words, the more you embellish the lie, and the more believable you make it, the more likely you are to confuse yourself later that it truly happened. If you created a whole litany of things that occurred at John's house that night in high school, the better to deceive your mother, then you are more likely to misremember that lie as the truth in the future.

Chrobak said that if a lie or fabrication provides an explanation for something, it's more likely to become confused with what's true. "People are causal monsters," he told me. "We love knowing why things happen," and if we don't have an explanation for something, we "like to fill in the gaps." The pressing human need to fill those gaps, Chrobak said, might also pertain to beliefs we hold about ourselves. After his arraignment on 13 criminal counts, Santos told reporters he believed he was innocent. "I will not resign," he said, "I'm gonna fight the witch hunt." If people see themselves as persecuted, then their lies might take on even greater significance for themselves—they become proof of their innocence.

Another important factor underlying this effect is repetition. "If I tell the lie to multiple people," True explained, "I'm rehearsing the lie." And rehearsing a lie seems to enhance it. "The more you repeat something," Chrobak said, "the more you actively imagine it, the more detailed and vivid it becomes," which further exploits the brain's tendency to conflate detail with veracity.

Further, Polage explained, "the more you access a memory, the more likely it is to be altered." If someone is lying, Polage said, then "every time they access the false memory, they add detail to it, they strengthen it, they become more confident in it, and they might become more confident that the false memory they are building is actually true."

But "it's not only what you rehearse, it's what you don't rehearse," True said. When lying, you're also not rehearsing the authentic details. "If you don't access a memory," Polage said, "the level of detail in the memory fades. You're strengthening the false memory and weakening the real one."

I suggested to True that because memory is essentially reconstructed or reassembled whenever we remember, fabrication might use similar neural pathways. If the brain uses the same circuits for both, it might be easier to confuse the two. "I think that's a great way of putting it," True said, mentioning that some research suggests that the neural circuitry involved in imagining an event is also employed in remembering one. "This is memory functioning as it should," Polage said, but "we're messing it up" with lies. "We give the false memories the characteristics of true memories, and so we blur the line."

I asked Chrobak if he thought people in positions of power and authority come to believe their own lies. "Yes, absolutely," he said. "This is on psychologists' radars now. People need to talk about this and why this is happening. A percentage of Americans believe demonstrably false lies. Whether they're their own or politicians', figuring out why this is taking place is relevant to our democracy. It's really important." That's no lie.

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REFERENCES

1. Loftus, E.F., Miller, D.G., & Burns, H.J. Semantic integration of verbal information into a visual memory. *Journal of Experimental Psychology: Human Learning and Memory* **4**, 19-31 (1978).

2. Loftus, E.F. & Pickrell, J.E. The formation of false memories. *Psychiatric Annals* **25**, 720-725 (2013).

3. Ackil, J.K. & Zaragoza, M.S. Memorial consequences of forced confabulation: Age differences in susceptibility to false memories. *Developmental Psychology* **34**, 1358-1372 (1998).

4. Pickel, K. When a lie becomes the truth: The effects of self-generated misinformation on eyewitness memory. *Memory* **12**, 14-26 (2004).

5. Polage, D.C. Fabrication deflation? The mixed effects of lying on memory. *Applied Cognitive Psychology* **18**, 455-465 (2004).

6. Polage, D.C. Fabrication inflation increases as source monitoring ability decreases. *Acta Psychologica* **139**, 335-342 (2012).

7. Polage, D. The effect of telling lies on belief in truth. *Europe's Journal of Psychology* **13**, 633-644 (2017).

8. Chrobak, Q.M. & Zaragoza, M.S. Inventing stories: Forcing witnesses to fabricate entire fictitious events leads to freely reported false memories. *Psychonomic Bulletin & Review* **15**, 1190-1195 (2008).

9. Johnson, M.K., Hashtroudi, S., & Lindsay, D.S. Source monitoring. *Psychological Bulletin* **114**, 3-28 (1993).

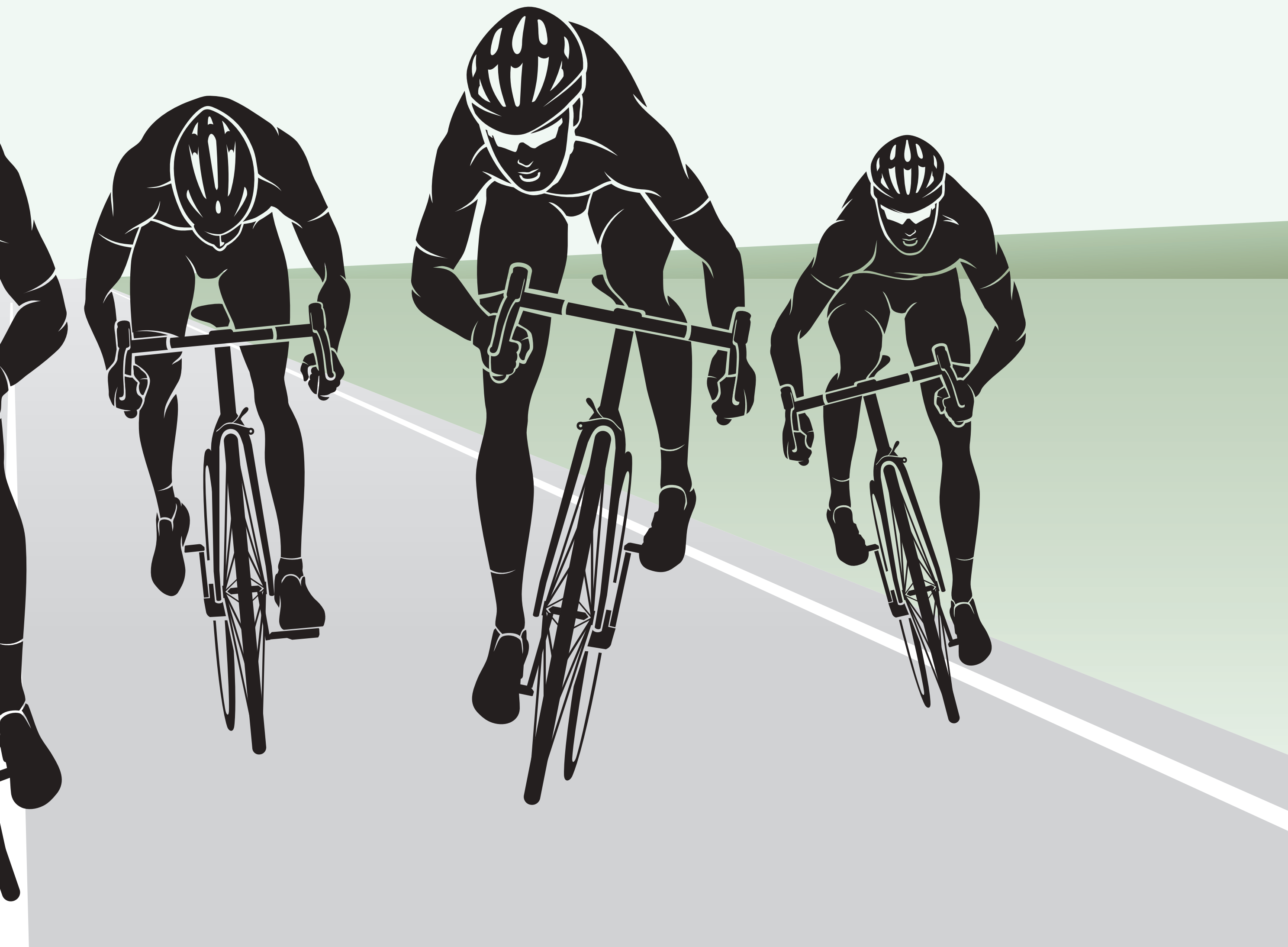
Winning By a Hair

For cyclists, it's a drag when you don't shave your legs

BY CHARLES DIGGES

W**HEN I FIRST GAVE UP** my running shoes for a road racing bike in 2016, I was confronted by a scroll of unspoken rules I would be expected to follow if I were to be taken seriously as a congregant in the Church of Cycling.

The edicts were compiled by the Velominati—an anonymous cycling cognoscenti that presents them as holy writ. Cycling shorts *must always* be black, though socks can be any color you like. The color of your saddle, however, *must* match the color of your handlebar tape and tires without exception. Which is to say, these, too, *must always* be black because tires only come in one color. And so it was for pre-ride coffees: black only, preferably espresso. Anything dulled by milk was purely for the unsaved.



There were others. Never, under any circumstances, lift your bike over your head—it is undignified for the machine. If you are ever unfortunate enough to draw the number 13 at a race, it must be pinned to your jersey upside down. And speaking of bad luck, accidents are not to be spoken of unless they involved a visit to the emergency room. Road rash, scraped elbows, bruised hips, and other evidence of unexpectedly meeting the pavement are just part of the discipline.

PAGES 90-91: STUDIO77 FX VECTOR / SHUTTERSTOCK

Some rules were intuitive, like showing up for training rides on time because they start exactly when they are supposed to—and I have never known that not to be the case. Others were more bizarre, such as never putting a bike on a car's roof rack unless the bike is worth more than the car—and you might be surprised at how often that *is* the case.

Helpfully, these rules were emailed to me by my first serious riding companion, a multi-time state champ who took his coffee black, drove a $19,000 Volkswagen, and dragged me for months along rural roads until I was strong enough to compete in our city's weekend group rides.

Clearly, he told me, some of the rules are open to interpretation and convenience. But there is one that is not: Shave your legs.

There were no exceptions. Even the flamboyant Peter Sagan, then the world's most revered cyclist, was once chastised by the elder brethren of the sport for having the nerve to turn up at a race *au naturel*.

Who was I to disagree? It was a demand of my new culture. I bought a razor and have been shaving my legs ever since.

Every year, as the summer tradition of the Tour de France once again descends upon us, a few hundred million devotees of the sport will watch, parse, argue about, and rejoice over the frenetic three-week-long procession that's powered by some of the smoothest male legs on Earth.

But why, since the Tour began in 1903, have its participants shaved their legs? A matter of hygiene? An offering to the velo gods? Is it purely a question of peer pressure, guided by fear of wrath from the fussy deities on cycling's Mount Olympus? Or is there something more earthbound behind it—some matter of utility that the great-grandfathers of le cyclisme suspected long ago but couldn't quite articulate as they first dragged a razor up their shins?

As it turns out, there is. Shaven legs are much, *much* faster. It just took until this century to prove it.

MONSIEUR, THE MUSTACHE MUST GO Lucien Petit-Breton, who won the Tour de France in 1907 and 1908, looks quite sleek for his time, when many riders wore baggy clothes. Had he lost the facial hair, reducing the surface area on his body, he would have been faster still.

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IN 2012, AS A RECENTLY MINTED GRADUATE from the Massachusetts Institute of Technology, with a degree in mechanical engineering, Marc Cote came to Specialized, a dominant manufacturer of high-end bikes headquartered in California. Cote had a hypothesis: Bicycle frames, wheels, helmets, jerseys, shorts, and shoes were all conspiring to cost elite cyclists valuable seconds in aerodynamic drag.

Aerodynamic drag, Cote explained to me in a recent chat, consists of two forces—air pressure drag and direct friction (known also as surface friction or skin friction). Direct friction is the force that occurs when wind meets the surface of rider and bike, but is nearly insignificant at the comparatively low speeds a cyclist travels. However, it is critical to consider when designing, say, an airplane.

On the bike, air pressure drag is the main beast. A cyclist and their machine form a blunt ("bluff" in aero lingo) shape forcing the air to separate around them as they move forward. The harder the cyclist pedals, the more the air in front of him is compressed, meaning that the harder he pushes forward to overcome this resistance, the harder the air pushes back.

Once the air grudgingly parts around the rider, the battle is not over. As the rider moves forward, battering the air out of the way, the air behind him becomes less dense, forming a low-pressure zone, or vacuum, that literally sucks him backward. This is a formidable force. In fact, on a flat road, aerodynamic drag is by far the biggest obstacle to a cyclist's speed, accounting for 70 to 90 percent of the resistance felt when pedaling.

Reducing the surface area of the cyclist as he confronts the wind is therefore key. The more streamlined the design of an object, the easier it is for the air to close around it, thereby approaching the holy grail of aerodynamic design: laminar flow—that sublime moment when the air closes around a moving object without leaving a turbulent wake.

As there is little that can be done about the awkward shape of the human body—though it must be noted that most pro cyclists are tall and willowy and in constant battle with their weight—the design of the bike and the equipment the rider wears are critical to speed. The less that is flapping about in the wind, the smaller the surface area of cyclist and bike.

Who was I to disagree? It was a demand of my new culture. I bought a razor and shaved my legs.

This was an issue that the titans of yore hadn't much considered as they pulled their baggy woolen jerseys over their heads. In the 1968 volume *King of Sports: Cycle Road Racing*, envisioned by its author as the final word on training, British cyclist Peter Ward argued for comfort over style. Clothing that is "the least bit tight or restrictive" should be avoided, he wrote. Cycling shorts, he added, should be held up with "braces,"—British for suspenders—and be "slack and comfortable."

A few years later, in 1976, the Dutch pro cycling team TI–Raleigh ignored that advice and brought Lycra to the cycling mainstream. There hasn't been a need for suspenders since. Over the following decades, the fit of cycling apparel has moved steadily skin-ward, cementing the image of the spandex-clad road warrior in the popular imagination. But Cote still suspected that there were a few wrinkles yet to iron out.

By 2013, he and his colleague Chris Yu in the aerodynamic research and development department had cajoled their bosses at Specialized into taking an enormous and cost-intensive leap—building a multimillion-dollar cycling-specific wind tunnel to track down and eliminate those last little bits of turbulence in the quest for a faster ride. The results were—and continue to be—transformative.

Research in cycling aerodynamics—what Cote calls "the invisible science"—has led to helmets that make the head of the wearer look like it has collided with a flying saucer, and shorts and jerseys that are so tight that it takes imagination *not* to see the more subtle curves of the flesh. The clunky shoes of Ward's era have shed their laces for shrewder and smoother fasteners that don't cause the air to hiccup around them. Even socks can be woven in special configurations that reduce drag. And new techniques in molding carbon fiber—the lightweight DNA of modern race bicycle-making—has produced frames that would have been unrecognizable as recently as 2007, when Lance Armstrong and his U.S. Postal team were still riding what amounted to a collection of fused-together cylinders.

NONETHELESS, ALL THE TECHNOLOGICAL ADVANTAGES can't conquer the inevitable human bulk of the rider, who constitutes about 75 percent of the aerodynamic drag that cyclist-plus-bike must overcome. And that's where Cote's most surprising research comes in.

It began with Jesse Thomas, a Specialized-sponsored pro triathlete who dropped by Cote's wind tunnel in 2014 to dial in his equipment before an upcoming Ironman competition. He, Cote, and Yu ran through different experiments—one comparing wheels, another tires, yet another helmets and skin suits—and chose those that the tunnel data said caused the least amount of drag. Ironman races include a 112-mile bike ride wedged between a 2.4-mile swim and a marathon, so any seconds Thomas could massage out of his equipment would be critical.

Thomas had turned up that day much the way Peter Sagan had at that race in 2016, sporting a full shag up his calves and thighs, though neither he nor Cote had put much stock in that until after completing the tests.

So as more of a gag than anything else, he and Cote thought they would solve the age-old riddle posed by the ancients once and for all: Does shaving your legs make any difference at all? Thomas sheared his guns to see.

The first set of results caused Cote's jaw to drop. If the data were correct, Thomas could save 70 seconds for every 24.6 miles (or 40 kilometers, a standard time trial distance) he rode on the bike. This was an enormous time gain in a field of sports where victory is often decided by fractions of seconds and tenths of inches over a finish line.

So they tested Thomas again. And again. And the numbers kept showing the same thing.

It was a Eureka moment.

Over the next several weeks, Cote and Yu invited more of their cyclist and triathlete friends to come and test hairy, shave, and test again, developing along the way what they called a "Chewbacca scale"—a rating of 1 being a leg with relatively little natural hair all the way to 10, connoting a level of hirsuteness rivaling Hans Solo's simian sidekick.

Time savings varied slightly depending on where test subjects fell on that scale, but the results continued in each case to be profoundly faster—so much so that it seemed silly for any performance-minded cyclist to forgo shaving. This was the very definition of free speed.

What was remarkable here, said Cote, was this: Most prior work in aerodynamics had been conducted at much higher speeds and the results of those experiments implied that hairy legs might benefit cyclists, the bristly hair acting much like the aerodynamic dimples on a golf ball.

Those characteristic dimples create a thin, turbulent boundary layer of air that clings to the ball's surface. This allows the smoothly flowing air passing around

The Tour de France is one of the hardest tests of endurance that humanity has sadistically invented for itself.

it to follow the ball's surface a little farther around the back side of the ball, thereby decreasing the size of the ball's wake. This reduces turbulence behind it and lessens the area of that low-pressure zone that follows and sucks at cyclists.

But a golf ball driven by a PGA player can travel as fast as 168 miles per hour—far faster than the aspirations of even Tour cyclists. At average speeds between 20 and 40 miles per hour, the bigger factor for cyclists was the surface area of the body meeting the wind—and the surface area of a shaved leg is as much as 10 percent less than that of a hairy counterpart.

"At these speeds, reducing the surface area is the most important thing, and that surprised us," Cote told me. "Past studies assumed that hair would be insignificant or would work like those divots on the golf ball—but at cycling speeds it just adds to surface area." Cote determined shaved legs are the second most important aerodynamic adaptation a cyclist can make, the first being whether the rider choses to wear a skin suit—which, with its long sleeves, also covers the hair on the forearms.

Cote's results were never compiled and published in a scientific journal, but his and Yu's work has been quasi-peer reviewed by countless imitators, most recently this May by the Global Cycling Network, one of YouTube's most watched and slickly produced biking-dedicated channels. In fact, GCN has visited the topic at least five times since Cote uploaded his original videos. And each time, the results showed the same thing: Cyclists with shaved legs are faster.

***LE GRAND BOUCLE*, OR BIG LOOP**, as the Tour de France is nicknamed, is the grandest of the grand tours, drawing a viewership on television and in person along France's winding country roads and mountain switchbacks that dwarfs the Super Bowl. By all accounts, it is one of the hardest tests of endurance that humanity has sadistically invented for itself.

The Tour is also the grandest performance of cycling aerodynamics at work. The Tour de France is ridden by 12 teams and consists of four kinds of stages—flat stages, hilly stages, mountain stages, and time trials, which, confusingly, are ridden on different sorts of bikes and require different styles of riding.

For the first three, riders mount the more familiar-looking road bike, with its ram's horn handlebars, and race together as a peloton, the first man over the finish line claiming victory. The time trials—of which a typical Tour only has one or two—are when each of the 198 riders are sent out on a course alone to race against the clock.

And it is on time trial bikes that the invisible science has had the most visible impact. Often resembling a wing turned sideways, riders mount these bikes dressed in skin suits, a torso hugging, long-sleeved singlet with low profile stitching. They then hunch over their machines with their elbows perched on aero bars, their arms held before them in the style of a praying mantis. Then they tuck their heads, capped in those absurd turbulence-reducing helmets, and go—each grain of sand through the hourglass a strike against them.

Road bikes, too, have evolved with the quest for aero. Round tubes have flattened out on their backsides and their leading edges have sharpened so that they pierce the air like a bullet. Seat posts are oval or teardrop-shaped and handlebars are flat in profile across the top and taper to an edge along the backside mimicking a wing. And deep-rimmed carbon wheels have long since replaced their skinny air-stirring aluminum alloy counterparts and offer yet further wind-rending advantages.

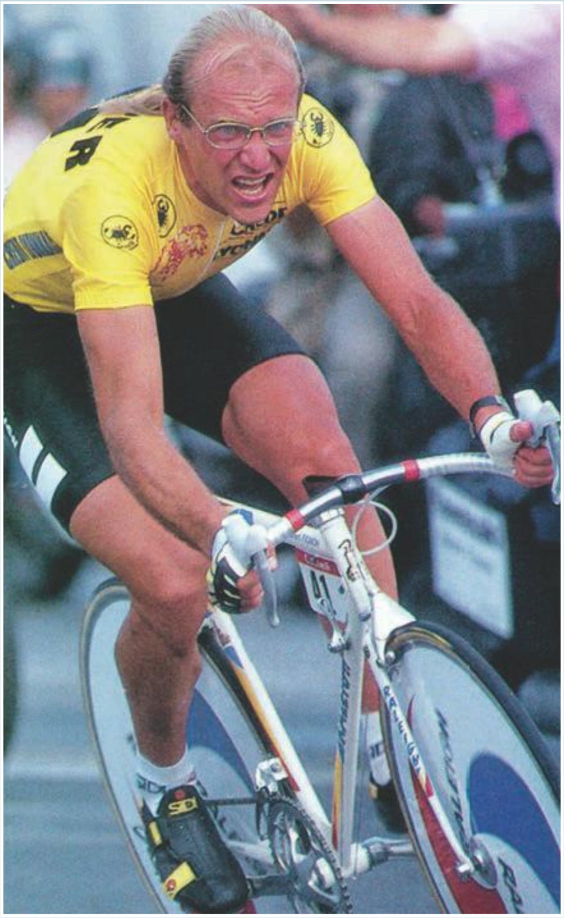
When the cyclists are on their road bikes racing in a peloton they take advantage of the aero modification as old as cycling itself—drafting. It is this technique that allows cyclists to capitalize on the turbulent low-pressure zones left by the cyclist riding immediately ahead of them. The low pressure behind the leading cyclist will help pull the following cyclist forward, while the vortices produced by the lead cyclist's wake will also swirl around the following cyclist and push him forward. So significant is the effect of drafting that cyclists who are riding in a group can save up to 40 percent in energy expenditure over a cyclist who is riding solo. Anyone who has ever cast their gaze skyward at a flock of migrating birds has seen aerodynamic drafting in action.

All the technological advantages can't conquer the inevitable human bulk of the rider.

On the ground, the technique is most apparent in the so-called lead-out trains preceding the final sprints in the Tour's flat stages. In these chaotic charges, it's easy to spot the jerseys of each team forming monochromatic lines as they weave through the peloton.

The idea is that several team members will burrow through the air for their designated sprinter, who sits on their wheels as the riders in front of him provide a wake full of those helpful vacuums and eddies. One by one, the leading riders will take a turn at the front and dig as deep as they can, ratcheting up the speed before they peel off to the side, exhausted. Finally, the last leading rider will pull off, launching the sprinter at breakneck speed a few dozen meters from the finish line. But each of these trains must have a highly aerodynamic engine for the sprinter to have any hope at all.

The evolution of all this air-slicing technology is reflected in the average speed of the Tour itself, which has spiraled upward since the early days. Two-time victor Firmin Lambot of Belgium posted the slowest average speed in the 1919 Tour at 14.97 miles per hour. One hundred and four years later, Denmark's Jonas Vingegaard nearly doubled that in his 2022



GET A HAIRCUT Laurent Fignon lost the 1989 Tour de France by eight seconds, the closest margin in Tour de France history. An experiment by Marc Cote, a mechanical engineer and cycling expert, showed Fignon would have won had he cut his drag-causing ponytail.

ANDERS / FLICKR

Tour victory with an average speed of 26.1 miles per hour—all while having traversed 122,000 feet—more than four times the height of Mount Everest.

THE WORK OF COTE—who now works at Zwift, a virtual cycling app—and his copycats provides valuable data for amateur cyclists like me, who typically don't possess the deep pockets and sponsorship deals that a professional cycling team does, but nonetheless obsess over aero, take on debt to finance new bikes, race, and go on training rides. A 90-cent razor, Cote told me, might be the wisest investment I can make.

But in a sense, Cote's test results simply validate something that most serious cyclists will—out of superstition or a sense of deference or dogged adherence to the commandments of the Velominati—continue to do anyway, regardless of what the wind tunnel says.

Grasping for these seemingly insignificant advantages was something that the cycling gods of the past understood acutely. At the center of their logic was a simple truth: Whatever you think makes you faster probably does.

Fausto Coppi, the Italian cycling giant who dominated the Tour in the years following World War II, insisted that he be carried upstairs to his hotel rooms after every stage of the race to preserve the strength of his legs.

France's great Roger Rivière, considered the favorite for the 1960 Tour until he careened over a guardrail in the mountains on stage 14 in an accident that left him crippled, was known to inflate his tires with helium.

His countryman, the towering time trialist Jacques Anquetil, who claimed three Tour victories in the late 1950s and early '60s, used to take his water bottle off the cage on the frame of his steel Gitane rig and tuck it into his jersey pocket when confronted with a climb. (Another finding by Cote: you will shave off 38 seconds if you tuck your water bottle in the back pocket of your jersey instead of the bottle cage on the frame.)

And so the story goes, right through the calamitous drug scandals of the Lance Armstrong era, where Armstrong and much of his team—and indeed much of the peloton—blood-doped with human growth hormone to goose their performance.

But even in the years since the sport has cleaned up, there remains that search for a talisman, for the ineffable edge that will express itself at exactly the right moment and inch you over the finish line first. To acclimatize his respiratory system to the Tour's high mountain stages, German rider Tony Martin—who won numerous Tour stages but never the coveted general classification overall win—had his entire house converted into an altitude chamber.

Against such tactics, shaving your legs is the least you can do.

Because in the oral histories of cycling, passed down to me by the riders who taught me how to take my coffee, tales of losing by a hair are almost too painful to recount—such as when the U.S. cyclist Greg LeMond beat the Parisian powerhouse Laurent Fignon in the 1989 Tour's final time trial stage, giving LeMond the overall victory by a mere eight seconds—the closest margin in Tour de France history.

It was an age before wearing helmets in the Tour became compulsory, and Fignon's biggest enemy that day was not LeMond. It was his signature blond ponytail.

Cote and Yu tested it. They took a cyclist of Fignon's stature, put him and a bike in the tunnel, bent him into Fignon's tucked time trialing position, and topped him off with a wig that matched Fignon's flowing tied-back locks.

They turned on the wind. Then stopped it, cut off the ponytail, and tested again. The result?

"Fignon should have gotten a haircut," Cote said. According to the data, Fignon would have beat LeMond by four seconds had his ponytail not been flapping about in the wind, causing critical aerodynamic drag.

"You never stop grieving over an event like that," Fignon bitterly wrote in his 2010 autobiography.

Ever since I heard that story, I have started shaving my head, too.

CHARLES DIGGES is an environmental journalist and researcher who edits Bellona.org, the website of the Norwegian environmental group Bellona. He is also an amateur cyclist and owns too many aero-optimized bikes.

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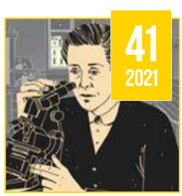

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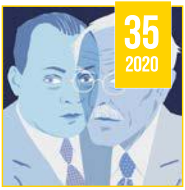
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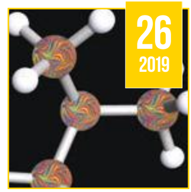
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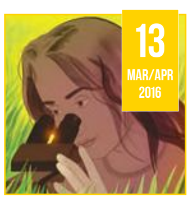
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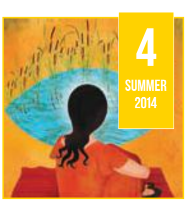
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Paul Nurse

The British Nobel Laureate on his roots, science, and Knighthood

INTERVIEW BY HERLINDE KOELBL

WORKING CLASS SKEPTIC

I came from a working-class, blue-collar family. So, it wasn't an academic background. There was nothing problematic about it, but I hadn't been exposed to books, to ideas, to culture. I was brought up in a home that was Baptist. I went to Sunday school, and I was a committed believer. I thought I might even become a preacher! But I got exposed to more of the world at school, and when I learned about evolution, the minister was not happy about the things I was asking him. I remember saying, "Can we not think of Genesis as a metaphor?" He just couldn't cope with that. That made me begin to doubt, and gradually I moved into my present position as a skeptical agnostic. An atheist is somebody who knows there is no God and no supernatural being. A skeptical agnostic is somebody who thinks it's very unlikely, but because it's supernatural and therefore beyond our understanding, how can you be sure?

NO SUCCESS LIKE FAILURE

I failed an entrance examination in French six times. Not once, not twice, but six times. I was trying desperately hard, and I couldn't pass! This was the late 1960s, and at the time that meant I could not get into any university in the United Kingdom. It was difficult, but in hindsight it was actually useful. I worked as a technician in the local Guinness Brewery, and that was important for me because I had a year of experience working in laboratories, which only strengthened my wish to work in that kind of environment. And that break was critical for me for another reason. I had failed early in my life, so I was no longer frightened of failure.

NOBEL DISCOVERY

What we discovered—my colleagues and myself, and also Lee Hartwell and Tim Hunt—was that there's a complex of molecules that make an enzyme, and this enzyme adds phosphate to other proteins. This can act as an important switch for different events in the cell. It meant that we now understood the basic process that controls growth and reproduction in the cells—in other words, the process that underpins growth and reproduction. Not just in humans but also in all every animal and plant you can see around you. And this has many applications, including those for cancer research.

MESSAGE TO THE WORLD

I would like the world to be a more rational and forgiving and tolerant place, and I think science can contribute to that. Science is essentially a rational activity. We should learn from the values of the Enlightenment, and we should apply them, including a tolerance of other people's thinking and thoughts. At the Francis Crick Institute, 70 percent of our scientists are from other countries, and any change to that means we're not utilizing the intellectual capital in the world. We need an openness to the world.

WHAT KNIGHT?

It came as a shock! In fact, the letter asking whether I would accept the knighthood was sent to the wrong address, so I never received it. Then one day, I had a call from 10 Downing Street, asking if it was my intention to refuse the honor? And I said, "I'm sorry, but I have no idea what honor you're talking about!"

Adapted from *Fascination of Science: 60 Encounters with Pioneering Researchers of Our Time.*

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