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The Rebel Issue

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ISSUE 55 Science Connected **NAUTIL.US**


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Volume One
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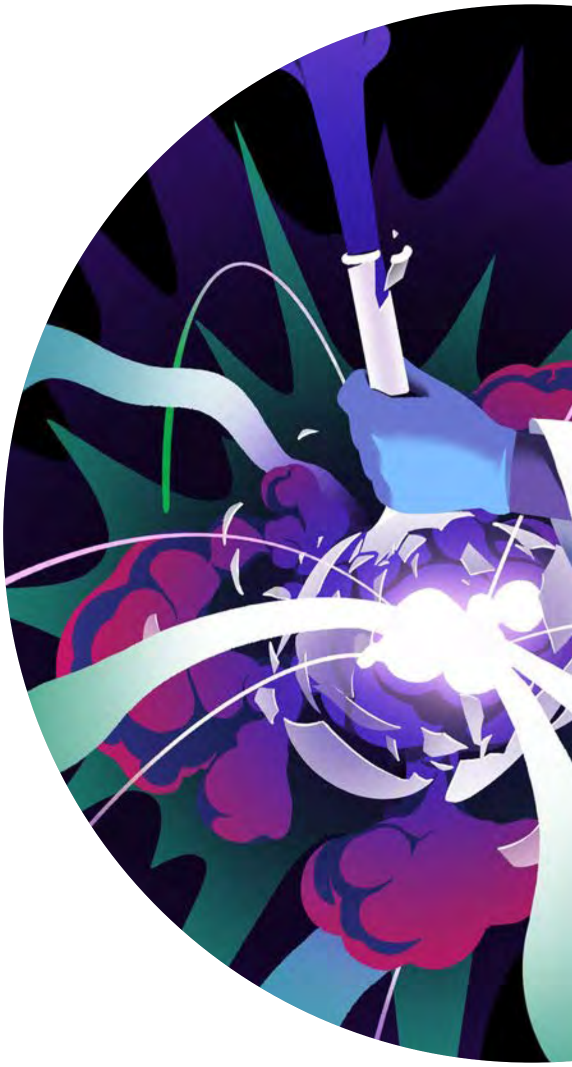

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CONTACT

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

info@nautil.us

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The Rebel Issue

BY KEVIN BERGER

GREETINGS, *NAUTILUS* READERS, and welcome to The Rebel Issue. In our own happy rebellion against the conventions of science writing, we've composed stories about rebels in science—unsung ones, mind you—and the subtle ways nature itself breaks with the past to create something new. The issue is about rebel, the noun and the verb.

Alas, there are no profiles of Galileo and Darwin, but the spirit of their scientific triumphs over superstitions infuses this special issue. And can I just say a few words about one of our guiding lights?

American psychologist Frank Sulloway wrote that "Darwin was born to rebel." But not in any way commonly associated with rebellion. He didn't wear a beret, as far as I know. Speaking of the French, Jean Pierre Flourens, a bigshot at the French Academy of Sciences, couldn't have been more offended at the publication of *On the Origin of Species* in 1859. Flourens' response gives you an idea of how Darwin's great book upended the stuffy thinkers of his time.

"What unclear ideas, what false ideas!" Flourens effused. "What metaphysical jargon clumsily hurled into natural history. What pretentious and empty language! What childish and out-of-date personifications! Oh lucidity! Oh French stability of mind, where art thou?"

Darwin was a country gentleman sensitive to nature like few before or after him. Freeman Dyson, a friend or colleague of many of the giants of 20th-century physics, including Albert Einstein, Wolfgang Pauli, Robert Oppenheimer, and Richard Feynman, wrote the common element of scientific visionaries "is rebellion against the restrictions imposed by the locally prevailing culture, Western or Eastern as the case may be." What made them rebel?

I just love what the understated Darwin wrote about himself. "As far as I can judge, I am not apt to follow blindly the lead of other men." How beautiful, and how apt of the scientists you will meet in this issue.

Barbara McClintock won the 1983 Nobel Prize in Physiology or Medicine for her discovery that genetic elements can change positions on a chromosome, which causes genes to be active or inactive. For 30 years, her findings about genetic transposition made her a pariah. Her colleagues, she once remarked, "thought I was crazy, absolutely mad." Did she care? She did not. Being shunned for years from conferences and committees was a blessing. "Instead of causing personal difficulties, this long interval proved to be a delight," McClintock said. "It allowed complete freedom to continue investigations without interruption."

As I mentioned, The Rebel Issue is not just about people. Nature knows no conventions. Evolution by natural selection can be seen as a perpetual rebellion against changing environments. This place will no longer do, organisms showed, we need to rebel. Revolutions followed. Take the case of microscopic cyanobacteria. It just happened to jumpstart an entirely new atmosphere, one with oxygen.

The philosopher and novelist Albert Camus wrote, "I rebel—therefore we exist." Rebellion is a form of hope, an act of creativity. "Of all the schools of patience and lucidity, creation is the most effective." Our stories in The Rebel Issue, created by journalists, scientists, and artists, show that hope is real, that rebellion really can change the world.


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“We are inhabitants of an ocean world. Everything that happens down there is linked to us up here.”
Dr Helen Czerski
Presenter, Ocean Matters
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THE PORTHOLE

Short sharp looks at science

PSYCHOLOGY

The Bad Trip Detective

TASNUVA ELAHI; WITH IMAGES BY MARTIN_MAILZ AND ANZHELIKAP / SHUTTERSTOCK

JULES EVANS WAS 17 YEARS OLD when he had his first unpleasant run-in with psychedelic drugs. Caught up in the heady rave culture that gripped '90s London, he took some acid at a club one night and followed a herd of unknown faces to an afterparty. There, he found himself pursued by a single thought, which followed him like a hunter's sights: He was behaving badly, and everyone in the room couldn't stop talking about him. A few months later, he started to experience bouts of panic and social anxiety, neither of which he'd ever felt before. "I was very worried that I'd damaged my brain, and that it was permanent," Evans recalls. He steered clear of psychedelics. But for the next six years, he suffered from panic attacks, social anxiety, dissociation, and depression, which only cleared after a course of cognitive behavioral therapy.

In 2017, Evans decided to try again. After learning of emerging research that suggested that psychedelics were safe in a guided setting, and in part to overcome his first traumatic experience, he traveled to a well-reputed retreat in Peru to take ayahuasca. Afterward, as he made his way to the Galápagos Islands, where he had planned a few days' peaceful reflection in nature, a strange feeling came over him. "I began to suspect that I was either in a dream of my own construction or trapped in some kind of fake reality constructed by someone else," he wrote in an essay in 2020. "Could I be in a coma or some afterlife limbo state?" The eerie feelings only intensified when he got to the Islands. On the ferry, he was convinced that he was crossing the River Styx into the land of the dead. "This isn't real," he thought to himself. "How do I wake up?" When concerned friends reached out, he thought his desperate subconsciousness was making them up. "I felt profoundly alone in this fake reality," he wrote. The ontological nausea faded 10 days later, but his doubts about the safety of psychedelics did not.

The psychedelic renaissance is upon us. In 2021, the National Institutes of Health's annual "Monitoring the Future" study observed that hallucinogen use had hit an all-time high since the first survey was completed in 1988, with reported use by United States adults aged 19-30 up to 8 percent. Following two decades of research celebrating the therapeutic potential of psychedelics, many people associate the substances with a range of psychological benefits: heightened social connection, reduced anxiety and depression, a deeper sense of meaning, and a more powerful connection to the divine or the universe.

But amid all the scientific and cultural enthusiasm for these drugs, little attention has been paid to bad trips and their after-effects, and even less to what might alleviate them.

The most serious effects may be vastly underreported in trials involving psychedelics.

This is not entirely arbitrary. Bad trips are rare: Surveys indicate that the majority of those who report having taken psychedelics never have a difficult or distressing experience, during or after the trip. But for a select few, the after-effects can be quite serious. In one small study of 613 psychedelic users, in the days and weeks following a challenging trip, close to 7 percent reported thoughts or attempts of hurting themselves or others, and 3 percent sought psychiatric help. Something called Hallucinogen Persisting Perception Disorder, flashbacks of visual disturbances that first arose during a hallucinogenic trip, is also now recognized by the DSM-V.

As Evans, now a researcher at the University of London in the Centre for the History of the Emotions at Queen Mary, began looking into the literature, he learned that the most serious effects may also be vastly underreported in trials involving psychedelics. One review of clinical ketamine use for depression, for example, found that 42 percent of serious adverse events and 39 percent of non-serious events reported in clinical trials data were not reported in the published articles. Some scientists say psychosis risk is also underestimated in the research literature, in part because older reports of it led modern psychedelic researchers to exclude participants with a family history of psychotic spectrum illness from their studies.

Evans decided to launch the "Challenging Psychedelics Project" with a handful of colleagues. They posted a survey in the fall of 2022, inviting people who had difficulties for at least a day following a psychedelic trip to participate. Some 608 individuals from around the world responded over the next few months, answering questions about context of use, the nature and duration of the challenges they experienced, plus a range of possible risk factors and perceived causes, and providing written accounts of their experiences. Evans was particularly interested in collecting written narratives about these bad trips, he says, which remain rare in the research literature.

In the resulting "cartography" of bad trips, published last October in *Plos One*—it has not yet been peer reviewed—Evans heard many answering echoes of his own experience. A majority of people reporting bad trips—about 75 percent—experienced emotional difficulties, primarily anxiety and fear, but also depression. Almost half struggled with existential confusion and "derealization," the sense that everything was unreal. Others struggled with issues relating to self-perception; they were plagued by excessive self-consciousness, or "depersonalization," a sense of being so detached from themselves that they viewed their own lives from a near-cinematic remove. Still others experienced social difficulties, a sense of disconnection from other people, problems with sleep and nightmares, and other physiological symptoms, such as breathing problems or heart issues, compulsive crying, experiences of psychosis. Five respondents experienced prosopagnosia, a difficulty recognizing faces.

For many of the respondents who took Evans' survey, the post-trip difficulties lingered for months or longer. One respondent wrote that his trip had "reset his soul" and left him feeling lonely and disconnected from others for 30 years. According to the study respondents, the negative effects were exacerbated by a lack of information about what was happening to them, which only increased feelings of anxiety, social disconnection, and existential confusion. More information could save a lot of people from unnecessary distress and psychological harm, says Evans.

Some of the respondents who suffered afterward had taken the drugs as part of a clinical trial or psychedelic therapy session, around 8 percent. "It might be surprising to the field, as leading scientists like David Nutt have argued that the risks of extended difficulties in clinical trials are basically zero," says Evans. This finding challenges the "set and setting" hypothesis of psychedelics, formulated long ago by pioneering psychology researcher and psychedelics champion Timothy Leary. That theory says that psychological mindset and environment powerfully influence a drug user's experience and that the intensity and duration of bad after-effects can be shaped by lack of preparedness, negative mindset, or a lack of psychological support. Another surprise: A prior diagnosis of mental illness did not predict the duration or variety of enduring difficulties.

Evans doesn't advocate against psychedelics. But by exposing the hazards that tripping could involve, Evans hopes to temper the prevalent ethos of breezy optimism with a dash of caution.

—*Shruti Ravindran*

ASTRONOMY

Could Modified Gravity Kill Planet Nine?

FOR EIGHT YEARS, astronomers have hunted for a mysterious "Planet Nine" on the edges of our solar system. Although no one's ever seen it, they've deduced its presence from observations of unusual clustering among asteroids found in the Kuiper Belt, a donut-shaped region of icy objects that is home to Pluto and most of the dwarf planets.

VADIM SADOVSKI / SHUTTERSTOCK

The Planet-Nine proponents argue that anomalies in the orbits of these so-called Kuiper Belt Objects are caused by the gravitational pull of the hidden Planet Nine—supposedly an ice giant up to 10 times as massive as Earth—as it traces an unusual, highly elongated orbit through our outer solar system. And they say that centuries of telescope observations have missed it because it's so far away—up to 30 times farther from Earth than Pluto—although dozens of teams around the world are involved in the search. In much the same way, anomalies in the orbit of Uranus led to the discovery of Neptune in 1846.

But now, a pair of researchers say they've gathered evidence that a controversial theory of gravity called Modified Newtonian Dynamics (MOND) can just as easily account for the strange orbits of the Kuiper Belt Objects. MOND was developed in the 1980s as an alternative way to explain discrepancies between general relativity and what astrophysicists were observing in galaxy-scale dynamics. However, it has remained a scientific underdog ever since.

"We took the theory, and boom—it explained all of these things," says astrophysicist Harsh Mathur from Case Western Reserve University. "We didn't tweak it in any way." Mathur and his co-author Katherine Brown, a theoretical physicist at Hamilton College, published their observations in a study in *The Astronomical Journal*. If MOND is correct, the researchers say, the Kuiper Belt Objects are pulled not by Planet Nine but by the gravity of the tens of millions of stars packed into a dense core in the Milky Way.

MOND proposes that gravitational forces deviate from Newton's and Einstein's predictions. According to MOND, these deviations become significant only on galactic scales, and can explain many phenomena we currently attribute to dark matter. If MOND is correct, dark matter doesn't exist.

"I'm definitely not ready to say 'I believe in MOND,' " says Brown. But "I believe in the analysis we did—and that analysis shows MOND is as good at explaining" the orbits of the Kuiper Belt Objects, as a hypothetical Planet Nine.

If MOND is correct, dark matter doesn't exist.

whole business as agnostic, and we remain agnostic," Mathur says. In fact, they set out expecting their findings would disprove MOND. They first calculated what they'd expect to see if MOND was correct—that the elliptical orbits of the most distant Kuiper Belt Objects would align with our galaxy's core. The researchers then compared their calculations to observations; and found that the observations agreed.

Most astronomers prefer the theory of dark matter over MOND. Dark matter is thought to form invisible halos around galaxies and clusters of galaxies, and vast filaments between them. Scientists calculate that dark matter makes up more than 85 percent of the mass in the universe, while visible matter is just the froth of our cosmos.

Proponents believe dark matter accurately explains all gravitational phenomena, whereas MOND does not. Dark matter can account for gravitational lensing by galaxies and galactic clusters, for example, where their immense gravity bends and magnifies light from more distant objects. MOND, they argue, can't explain the behavior of some galaxy clusters. But MOND proponents argue that better observations or refined mathematics might account for any discrepancies, and anyway, efforts to determine what dark matter is made of and to detect it directly have turned up nothing.

Brown and Mathur say they aren't willing to stake a claim about MOND's veracity, yet: "We approached this

"We find in MOND that those outer Kuiper Belt Objects should line up, which is basically the signal of the Planet Nine hypothesis," explains Mathur. In other words, the gravitational pull thought to come from Planet Nine can also be explained under MOND by the pull of the stars in the center of the Milky Way. But the direction is arbitrary for Planet Nine, Mathur says: "They just put it where they needed it." So either Planet Nine is currently in orbit somewhere in the outer reaches of our solar system, or the predictions of MOND are correct.

The researchers say more observations should help to sort out what's driving the Kuiper Belt anomalies. "Over the next five to 10 years, we should see whether this alignment continues to hold up as more Kuiper Belt Objects are discovered," Brown says. "Our analysis leaves that open, and I think that will be one of the forks in the road."

—Tom Metcalfe

HISTORY

The Age of Rebellion

WHEN GEORGE WASHINGTON was a young man, he was far from the level-headed statesman depicted in paintings and books from the Revolutionary War era. Born in 1732 into a second-tier Virginia family, Washington was drawn to a military career as a way to propel himself upward—with ambition that bordered on the lunatic. By 20, he was a colonial militia leader, described as "temperamental, vain, thin-skinned, petulant, and awkward." He was emotionally needy and prone to making mistakes.

Those errors caused an international uproar when Washington, acting without orders, tracked down and attacked a small mission led by the French with no provocations, slaughtering 35 French soldiers in their tents. His actions set off a skirmish that would become the seven-year French-Indian war.

But by the time the Revolutionary War started two decades later, Washington was 45. The leader of the American rebellion had matured. He'd learned from his hot-headed early days. "He was able to master and control some of his personality from his earlier years,"

UNCLE LEO / SHUTTERSTOCK

Young rebel leaders were the most likely to lose.

explains Daniel Silverman, a political scientist at Carnegie Mellon Institute for Strategy & Technology. Silverman and two colleagues used Washington as a case study in a paper that analyzes how the age of rebel leaders impacts their success in military operations.

The researchers assessed the careers and wars fought by 425 rebel leaders throughout history and around the world and found some major themes: Young rebel leaders were the most likely to lose, middle-aged rebels were most likely to find military success, and older rebels were most likely to reach negotiated settlements.

Rebels are generally weaker than the governments they're fighting, Silverman points out, which means they have to be creative. "You need to know how to pick your battles, how to take advantage of opportunities," he says. "There's a lot of decision making and marshaling resources instead of going for a maximum brute force approach, as you could if you were more powerful."

The results point to a few universal truths about age and maturity—especially for men, as all but one of the leaders in the study were male. Young men can be prone to hot-headed behavior, especially in situations where they are provoked and need more common sense and patience.

Young men between the ages of 15 and 30 commit the most acts of criminal and political violence around the globe, which the authors attribute to testosterone, which peaks in males in their mid 20s and falls off afterward. That puts young men at a disadvantage as rebel leaders, where restraint is more important than impulsivity. Older leaders, they argue, are more likely to see the bigger picture in their actions, and are better able to regulate their emotions.

Silverman sees some potential applications to the research: It would be helpful for governments and peacemakers to understand that if someone takes over a rebel organization at a very young age, they might be especially dangerous and prone to violence. "They're likely to push the escalation button if they're challenged, and that could lead to some dangerous places," he says. "So maybe there should be a little more understanding of the risks there."

Kathleen Gallagher Cunnighman, a political science professor at the University of Maryland, says that the evidence in the paper is interesting and the analysis is sound—but that the research doesn't speak to the underlying biological process they advance in their theory. She also notes that the outcome is aggregated—focused on the final winners instead of looking at individual rebel events. "I would be interested to see data on actual battle outcomes," she says, "rather than war end outcomes to compare young leaders to other leaders."

Silverman says that while age matters in the context of rebel leaders, it can be overridden by other factors: The context of the conflict is important, of course. Some research has shown that if a leader starts a conflict rather than inheriting it from someone else, they are more likely to cling to it and not compromise, no matter their age.

In Washington's later years, he was insistent on treating British POWs humanely and avoiding theft from and harm to local farmers, even while his soldiers were starving. This restraint, gained from age, ultimately won him clear-eyed victory, as well as a storied place in history.

—*Katharine Gammon*

ASTRONOMY

Nine Rebel Astronomy Theories That Went Dark

THE HISTORY OF ASTRONOMY has hinged on radical ideas that transformed our understanding of the cosmos and our place in it. The most obvious of these may be the discovery in the 16th century that the Earth and other planets orbit the sun. An unpopular idea when it was first proposed, today it is so fundamental to basic astronomy it is practically taken for granted. But our most brilliant scientists have also floated some wild ideas that were not only unpopular at the time—they also turned out to be incredibly wrong. Some of these wrong ideas led to other important discoveries, however, that were very right. Here are a few of astronomy's fallen angels for your enjoyment.

SERGEY NIVENS / SHUTTERSTOCK

1. KEPLER'S PLANETS

The pioneering 16th-century German astronomer Johannes Kepler proposed in his book *Mysterium Cosmographicum*, published in 1596, that the gaps between the planets could be explained in terms of the five "Platonic" solids: These were "regular" polyhedrons with four, six, eight, 12, and 20 faces that Plato hypothesized could describe the shapes of all of the elements on Earth. According to Kepler's theory, the planets' orbits were dictated by these five different shapes: The orbit of Venus, for example, fit within a 20-sided icosahedron, the orbit of the Earth fit within a 12-faced dodecahedron, the orbit of Mars within a four-faced tetrahedron, and so on. This scheme produced six layers, each nested inside the other, which Kepler claimed corresponded to the orbits of the six known planets at the time.

Later observations showed his proposal was entirely wrong, but the idea brought Kepler to the attention of the Danish astronomer Tycho Brahe. Tycho was then working in Prague for the Holy Roman Emperor and invited Kepler to become his assistant. When Tycho died about 18 months later, Kepler became his successor as Imperial Mathematician. The appointment gave Kepler access to Tycho's observations, which he eventually used to formulate his laws of planetary motion.

2. THE LUMINIFEROUS AETHER

Many physicists in the 19th century thought the universe was filled with an unseen medium called the "luminiferous aether" (or ether) that allowed light to propagate as waves. The famous Michelson-Morley experiment in 1887 finally proved this wrong, by determining the aether didn't make any difference to the speed of light when the Earth was at different points in its orbit. As a result, physicists sought new explanations for the behavior of light, which led to Albert Einstein's special theory of relativity in 1905.

3. A TRIPLE SATURN

The Italian astronomer Galileo Galilei didn't know what he was seeing when he first observed Saturn through a telescope: "The star of Saturn is not a single star," he wrote in 1610 "but is a composite of three, which almost touch each other." What he was seeing was Saturn's rings, but nobody expected planets to have rings back then. Galileo's idea that Saturn consisted of a single planet with two large moons that almost touched it on either side—something never before imagined—lasted until 1659, when the Dutch astronomer Christiaan Huygens proposed that the observed changes in Saturn's shape were caused by Earth's view of its rings as the planet slowly changed its tilt.

"The star of Saturn is not a single star," Galileo wrote in 1610 "but is a composite of three."

4. BINARY STARS

Early sky-watchers like the German-British astronomer William Herschel explained their many observations of "double" or "binary" stars as tricks of alignment, supposing that one of the stars was much farther behind the other. But in 1767, the English scientist John Mitchell—a friend of Herschel—showed mathematically that there were far too many observations of double stars for such alignments to occur at random; instead, he reasoned, the stars must be relatively close and bound together by their gravitational pull. Mitchell asserted that stellar clusters, too, couldn't be the result of random alignments, and calculated that there was only about one in half-a-million chance that the Pleiades cluster, made of more than 1,000 stars and sometimes known as the Seven Sisters, could have formed randomly. Mitchell's work was the first application of statistics to astronomy.

5. THE PLANET CERES

After Ceres was discovered in 1801 by the Italian priest Giuseppe Piazzi, astronomers around the world hailed it as a new planet—the first detected inside the orbit of Jupiter since antiquity. Ceres occupied a gap in the solar system where the 18th-century Titus-Bode law suggested a planet should reside. Piazzi initially declared that Ceres was only a comet, but admitted in a letter to a friend that he thought it might be a planet instead; later observation suggested his suspicions were correct. But the discovery of Pallas—the third-largest asteroid in the solar system—and other objects in roughly the same orbit soon established that Ceres was one of many "asteroids"—a term coined by Herschel. It is now classified as the only "dwarf planet" in the inner solar system.

6. THE CANALS OF MARS

One of the first to see lines on the surface of Mars was the Italian astronomer Giovanni Schiaparelli, who in 1877 said he'd observed seas and continents connected by linear structures, which he called *canali*. Schiaparelli seems to have thought the lines were natural—the word *canali* means "channels" in Italian. But the idea that they were artificial canals became widespread and culminated in three books written by the pioneering American astronomer Percival Lowell. Lowell proposed there was a vast network of irrigation canals on Mars that could only have been built by intelligent Martians. But observations by NASA's Mariner space probes in the 1960s showed no such features, and it now seems the Martian canals were an optical illusion.

7. THE STEADY-STATE THEORY

Almost all cosmologists now subscribe to the Big Bang theory, which proposes the universe began with the sudden expansion of a "cosmic egg" about 13.8 billion years ago. But many 20th-century theorists—including the eminent English astronomer Fred Hoyle, who developed the theory of stellar nucleosynthesis—preferred the steady-state theory, which proposed that the universe had no beginning and no end. Under the steady-state theory, new matter was continually being created in voids between stars and galaxies, thereby maintaining the density of matter in the expanding universe. But it was at odds with observation that found only newer galaxies at the edges of the universe; and it fell from favor after the 1964 discovery of the cosmic microwave background, which had been predicted by the Big Bang theory.

8. ALIEN RADIO

The discovery of the first pulsar—a "pulsating radio source"—by the Northern Irish astrophysicist Jocelyn Bell in 1967 was a perplexing development: No one could imagine how such a powerful radio source could repeat every one-and-a-third seconds. Bell's discovery of a second pulsar a few weeks later quashed the notion that this was a radio signal from an alien intelligence; but the idea seems to have been taken seriously, at least for a day or two, and the first pulsar was given the name "LGM-1," for "little green men." Astronomers soon identified pulsars as rapidly rotating neutron stars.

9. A PLANET FOR BARNARD'S STAR

In the 1960s, the Dutch astronomer Piet van de Kamp announced he'd detected the first planet beyond our solar system around Barnard's Star—a red dwarf relatively close to Earth and the fastest-moving star in our sky. Van de Kamp based his idea on wobbles in the star's path, which he proposed showed the tug of an orbiting planet at least three times larger than Earth. Van de Kamp's method had some similarities to the radial velocity method now often used to detect exoplanets. Radial velocity is measured by observing the gravitational wobbles on a star caused by their orbits. But astronomers determined that van de Kamp's claims were in error; and while later observations have suggested there might indeed be an exoplanet around Barnard's Star, it would have been too small for van de Kamp to have detected it.

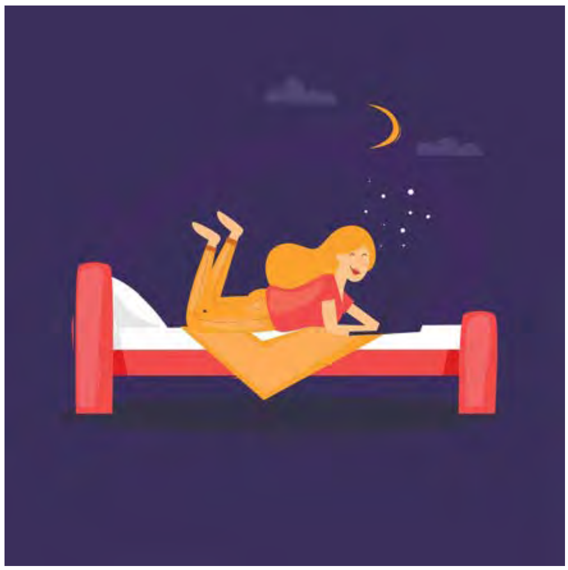
—*Tom Metcalfe*

PSYCHOLOGY

When Sleep Deprivation Is an Antidepressant

MY DEFAULT MODE FOR WRITING term papers during my student days was the all-night slog, and I recall the giddy, slaphappy feeling that would steal over me as the sun rose. There was a quality of alert focus that came with it, as well as a gregariousness that would fuel bonding sessions with my other all-night companions. After we'd turned in the products of our midnight oil to our professors, we would all head out for pancakes. Then I'd go home and sleep the magic off.

For years, I'd wondered if there was any basis for this temporary euphoria that I—though certainly not all my classmates—experienced after those sleepless nights. That I should feel so expansive and goofy after skipping sleep while many of them turned into drowsy grouches seemed to defy logic. Going without sleep isn't supposed to be a good thing, especially for folks who experience depression, as I have.



PODIS / SHUTTERSTOCK

But it turns out this paradox has been the subject of inquiry for at least two centuries. In 1818, University of Leipzig psychiatrist Johann Christian August Heinroth was reportedly the first to suggest that partial or total sleep deprivation could be temporarily effective against "melancholia," as depression was called in those days. He found this to be true only in a certain subset of patients—around 60 percent. More than 150 years later, in the 1970s, evidence emerged that a "resynchronization" of disturbed circadian rhythms could be responsible for the improved moods of depressed patients after a night without sleep. And more recently, researchers have found that a neurotransmitter involved in reward known as dopamine may play a role in this effect, as may neuroplasticity—the nervous system's ability to rearrange itself in response to stimuli. But the precise neural mechanisms responsible have remained unclear.

Last summer, Philip Gehrman, a professor of clinical psychology at the University of Pennsylvania, and his colleagues, published a study in the *Proceedings of the National Academy of Sciences* that provides further evidence for the phenomenon and suggests that closer connections between certain brain regions may have something to do with it. The researchers found that one night of total lack of sleep can temporarily boost mood in some healthy and depressed people, and that these individuals show greater connectivity between the amygdala, which processes emotion and memory, and the anterior cingulate cortex, which is responsible for decision making and learning.

> One night of total lack of sleep can temporarily boost mood in some people.

Gehrman warned me that none of us—especially those suffering from depression—should try to self-medicate by pushing through until dawn. But he says his findings could help scientists identify other forms of therapy for the condition, which is so difficult to treat. "What our results suggest is that therapeutic sleep deprivation may directly target these circuits," says Gehrman. "If we can find a way to target those circuits in ways other than with sleep deprivation, it may be possible to develop treatments for depression that are both rapid but more sustained than sleep deprivation."

One of these, Gehrman proposed, might be an approach known as transcranial magnetic stimulation, which uses magnetic waves delivered from outside the skull to stimulate nerve cells in the brain involved in mood control. Thus far, such treatments have been tricky to use because the magnetic waves have to hit very precise areas of the brain to be effective. Still, Gerhman says that circuits that respond to sleep deprivation could potentially serve as valuable future targets for magnetic stimulation, though this approach would need to be tested in clinical trials first.

For the study, Gehrman and his team evaluated 30 people with major depressive disorder while they underwent sleep deprivation. He also observed another 54 people without depression, 16 of whom slept normally throughout the study and were used as controls. Over a five-day period, Gehrman and his colleagues performed three resting-state-functional magnetic resonance imaging—or RS fMRI—scans on all participants to track blood oxygen delivery to the brain.

The two groups who were deprived of sleep—depressed and healthy—underwent an fMRI scan after a normal night's sleep, another after a night of sleep deprivation, and then a third after two subsequent nights of normal sleep. The 16 non-depressed control subjects went through the same series of scans but slept normally all four nights. Throughout this period, when awake, the participants completed questionnaires to assess their moods every two hours. A little less than half, or 43 percent, of the depressed participants reported a mood improvement after staying up all night. But most of those who didn't suffer from depression said their moods got worse.

Just as curious as the antidepressant effect of staying up all night is the fact that not everyone can experience it. Stanford neurologist Robert Sapolsky, who has long studied the biology of depression and sleep, confessed in an email that the results of the Gehrman and other studies "seemed completely counterintuitive to me, insofar as a wide range of chronic stressors (e.g., sleep deprivation) bias toward depression."

Nevertheless, he finds the idea hard to dismiss. "It's solid and replicated," Sapolsky wrote. "I think the keys are that it is only a night's worth, isn't long lasting, and only works in a subset of people. Real progress will come when people figure out what it is about that subset that matters."

Gehrman acknowledged that what separates those for whom therapeutic sleep deprivation is effective and those who just get cranky and want to go to sleep is a mystery as old as Heinroth's first observations of the effect.

"A number of people have tried to figure out what is different between 'responders' and 'non-responders' but no convincing patterns have been found yet," he told me. Even with their own findings, it's difficult to know which comes first—higher connectivity between the two brain regions, or improved mood. "We focused on the circuit-level changes, but those changes may have occurred because of underlying changes in dopamine activity," Gehrman says. Either way, he and his colleagues believe that neuroplasticity likely has something to do with it.

As I type this in the wee hours before sunrise, I'm feeling pretty good about Gehrman's findings—and about the sun coming up.

—Charles Digges

MICROBIOLOGY

When Bacteria Are Beautiful

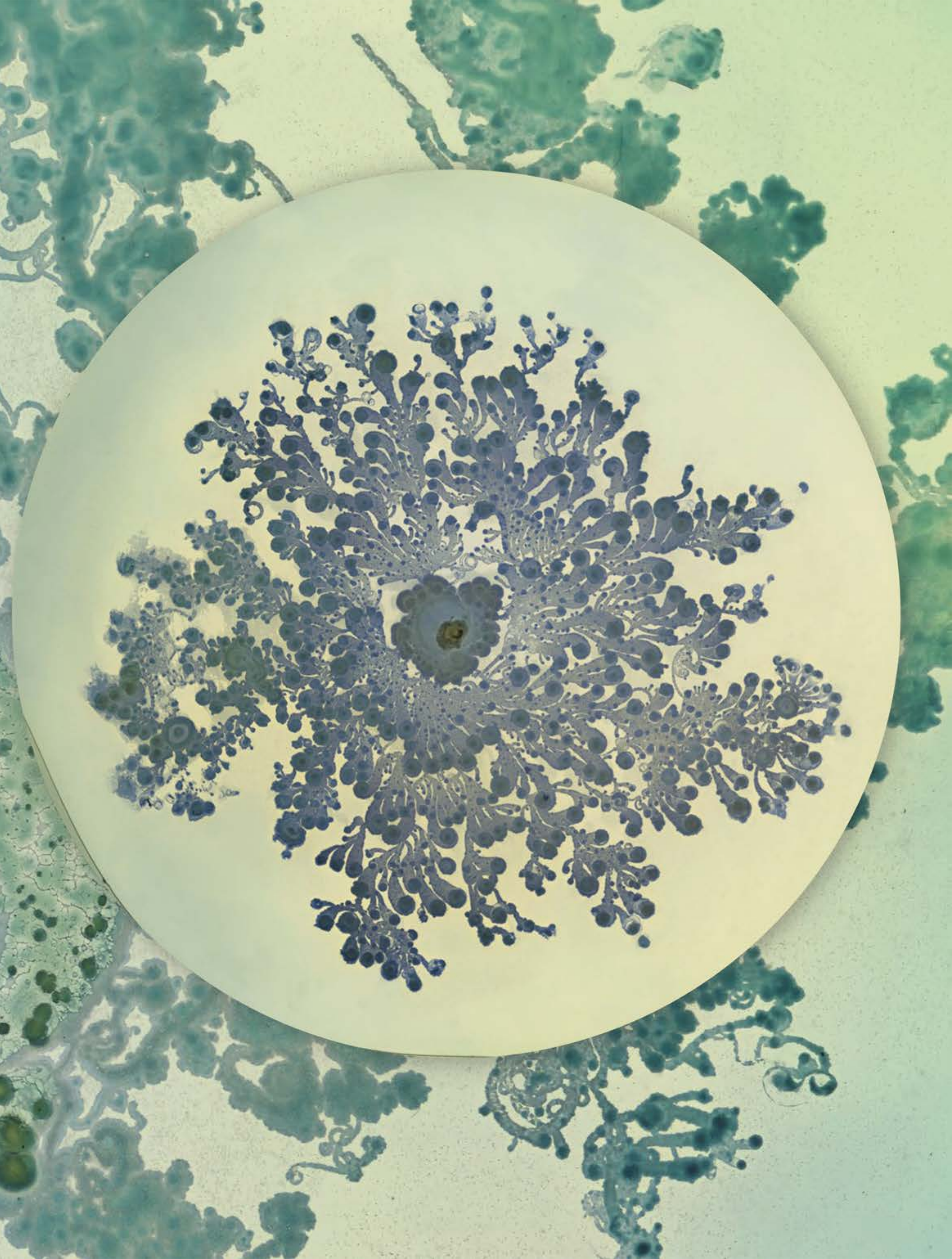
"AESTHETIC BEWILDERMENT" is a kind of common ground in science and art, an engine for new ideas in both disciplines, writes Brazilian artist Vik Muniz in the introduction to a new book of photographs and essays about bacteria by microbiologist Tal Danino: *Beautiful Bacteria: Encounters in the Microuniverse*.

Danino collaborated with Muniz on a number of projects—including one that involved making art out of viruses and cancer cells—when Muniz was a visiting artist at MIT. "I think that scientists often see a beautiful pattern and wonder about the underlying processes that make such a pattern happen," says Danino when I ask him what aesthetic bewilderment means to him.

It seems like the bedrock of Danino's new book: Here are the invisible microworlds so many of us take for granted brought to screaming life in flamboyant colors and electrifying geometries. Bacteria often inspire fear or disgust—particularly disease-causing pathogens such as *Escherichia coli* or *Staphylococcus*—but the beauty of these images draws the attention, provokes a desire to understand what the eye beholds.

— *Kristen French*

Isolates of *Paenibacillus* bacteria from California beach sand.
Photo by Tal Danino



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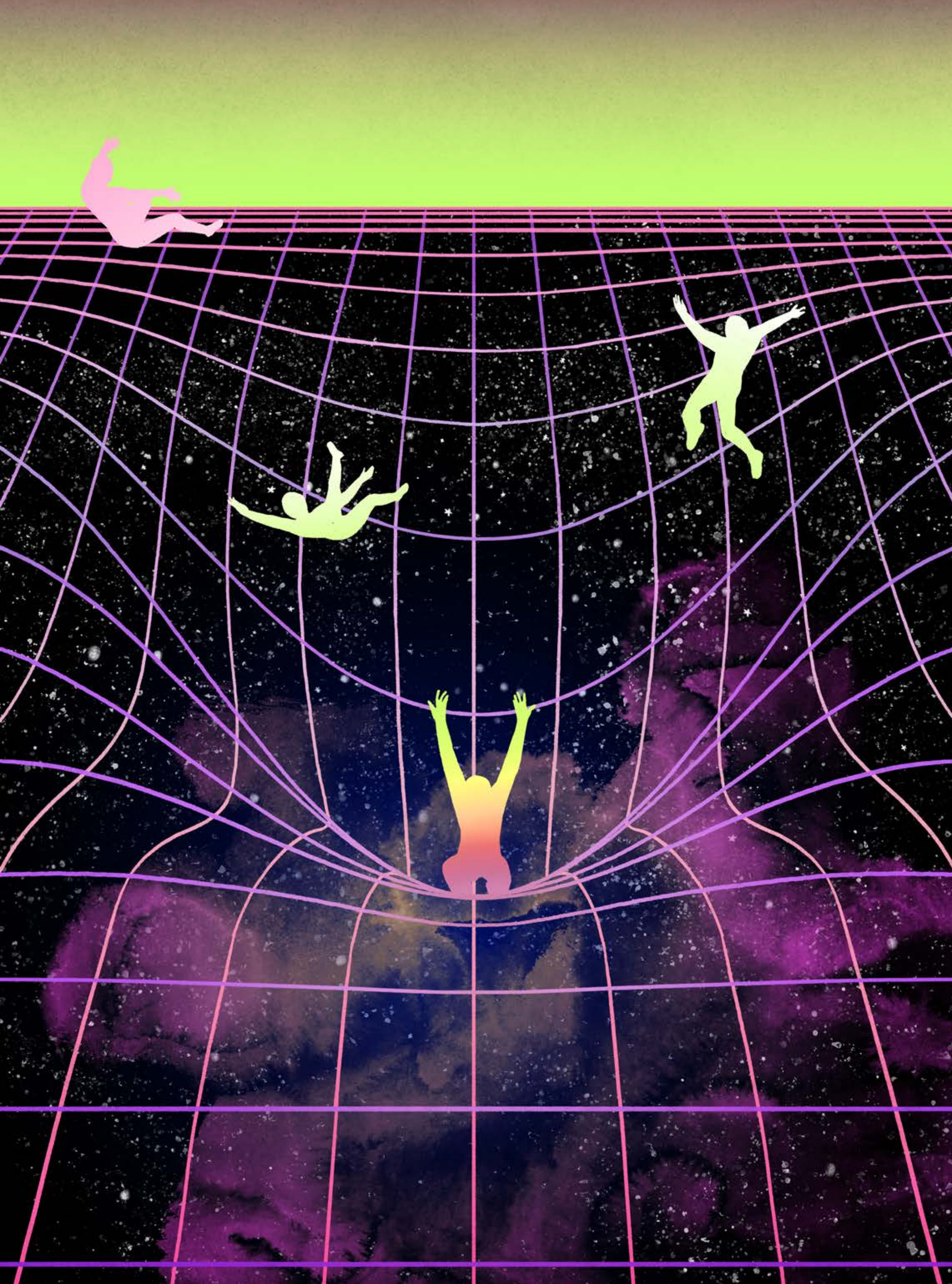


The Joy of Rebellion

BY KEVIN BERGER

EINSTEIN HAD BEEN LABORING for years over equations to prove his new theory of relativity. Gravity was not a force between particles of matter, proportional to their size and distance, as Newton calculated it, but the result of a curvature in spacetime. If Einstein could explain an anomaly in Mercury's elliptical orbit around the sun, he would have his eureka moment.

For decades astronomers had noticed the perihelion of Mercury's orbit—its closest point to the sun—had shifted about 43 seconds of arc per century, a fact that undermined Newton's view that the gravitational force maintained a steady orbit between sun and planet.

In November 1915, Einstein hit the mathematical jackpot. His gravitational field calculations showed that his theory of relativity could explain the tiny shift in Mercury's orbit. "I was beside myself with joyous excitement," Einstein said to his friend and colleague, Paul Ehrenfest.

Einstein is one of history's legendary rebels. And greatest wits. "To punish me for my contempt of authority, Fate has made me an authority myself," he wrote to a friend in 1930. In his biography of Einstein, Walter Isaacson writes Einstein's outlook made him "a rebel with reverence for the harmony of nature, one who had just the right blend of imagination and wisdom to transform our understanding of the universe."

In the features that follow in this, our Rebel Issue, you will meet a panoply of imaginative scientists with their own deadly wits and disdain for conventions. And you will encounter rebellions in nature itself, always evolving, never standing still. As it must, and we must. Down with authority!

ILLUSTRATION BY ANGIE WANG

COLLAGE BY TASNUVA ELAHI; WITH PHOTOS FROM THE NOBEL PRIZE

The Prizefighters

If you want to know what it takes to succeed in science, head to the Nobel Prize ceremony

BY MICHAEL BROOKS

G**UTSY. BLOODY-MINDED. IRRESPONSIBLE. DEVIOUS.** Cavalier. Reckless. Tough. There's a Nobel Prize for each of those characteristics.

The recipient of 2023's Nobel for Medicine was certainly gutsy. To stay in the United States in 1988, Katalin Karikó, born and raised in Hungary, had to fight an extradition order initiated by a slighted former colleague. When the University of Pennsylvania repeatedly demoted her because she wasn't bringing in enough money, she left, telling her bosses to preserve her lab as a museum, because one day her work was going to make her famous. She was right: Her research and insights paved the way for the COVID-19 vaccine.

Nobel laureates are often like that. While the public perception of science is one of a careful, modest, plod toward discovery, the truth is that scientists keen to make a difference in their field often have to upend things to change the status quo. Nobel laureate Sir Paul Nurse has likened his role within a research group to an adventurous special forces operative who gets dropped behind enemy lines to do difficult, dangerous work. In science, prizewinners are like prizefighters: larger than life risk-takers, fiercely driven competitors willing to push the rules to the limit—and break them if necessary. In his autobiographical sketch for the Nobel Prize, 2005 laureate Barry Marshall wrote that his bold experiment "was one of those occasions when it would be easier to get forgiveness than permission." And sometimes you have to bring that knockout punch: Your competitors are not going to stand aside and let you onto the podium unchallenged.

Katalin Karikó
Nobel Prize in Physiology or Medicine 2023

Barbara McClintock
Nobel Prize in Physiology or Medicine 1983

Marie Curie
Nobel Prize in Physics 1903;
Nobel Prize in Chemistry 1911

Stanley B. Prusiner
Nobel Prize in Physiology or Medicine 1997

Hannes Alfvén
Nobel Prize in
Physics 1970

Dan Shechtman
Nobel Prize in
Chemistry 2011

Barbara McClintock's bloody-minded pursuit of her big idea in genetics carried her past an array of jeering colleagues. One even referred to her as "just an old bag," but it didn't stop her bagging the 1983 prize in Physiology or Medicine for her discovery that genetic elements can change positions on a chromosome, which causes genes to be active or inactive. Kary Mullis could reasonably be deemed irresponsible in his Nobel-winning use of LSD to work out how to replicate DNA. Werner Forssmann was devious: He tricked a colleague into handing over the keys to his hospital's operating theater, where he performed a forbidden—but groundbreaking—experiment on his own heart. Stanley Prusiner was cavalier with the processes of science to establish prion proteins as the cause of the brain disorder, Creutzfeldt-Jakob disease—one colleague accused him of doing "horrendous things," and "just running roughshod over his field."

Barry Marshall was famously reckless. He swallowed a sickness-inducing cupful of *Helicobacter pylori* bacteria to prove that they, and not lifestyle issues such as smoking and stress, caused stomach ulcers. And Marie Curie was definitely tough, if only for showing up for the Nobel ceremony after the committee had explicitly asked her not to. She had been excoriated by the French press, because of her relationship with the physicist Paul Langevin, who was married. The Swedish academy didn't want their king to shake hands with an adulteress, but Curie was having none of it. "I cannot accept … that the appreciation of the value of scientific work should be influenced by libel and slander concerning private life," she told the academy, and made her way to Stockholm.

Curie's situation is perhaps unique among this list of Nobel laureates; her rebelliousness was not in her science but in her presence in Stockholm. The others, though, were rebels through and through. And for some, that nature even carried over into their Nobel Prize acceptance speeches.

Take Prusiner, for example. He certainly had an ax to grind: On the day the Nobel Committee announced his prize for showing that a protein lay behind scrapie, CJD, and mad cow disease, the head of neuropathology at Yale complained the award would stifle other lines of inquiry—and that a virus would ultimately be shown to be responsible for the diseases. The director of the federal Rocky Mountain Lab in Montana declared, "There is no direct proof that a protein alone is the infectious agent

Barry J. Marshall
Nobel Prize in Physiology or Medicine 2005

Kary B. Mullis
Nobel Prize in Chemistry 1993

Werner Forssmann
Nobel Prize in Physiology or Medicine 1956

(or that a virus isn't involved)." So when Prusiner got up in front of the academy, he made it clear that his colleagues had been short-sighted when they declared him unworthy. "Only a small number of people can grasp the meaning of such discoveries initially," he said. In case his detractors didn't get the barbed point, he wrote an autobiography that made it clear he had suffered a "torrent of criticism"; "the personal attacks of the naysayers at times became very vicious," he said. Ultimately, the rebel won—and enjoyed it. Perhaps more importantly, it has now become clear that understanding prion proteins matters: Their properties have been linked to the processes behind degenerative brain diseases such as Parkinson's and Alzheimer's.

Hannes Alfvén also indulged himself at the Nobel ceremony. An electrical engineer, Alfvén won his physics Nobel in 1970 after a decades-long fight against the physicists whose discipline he had invaded. Chief among his detractors was British mathematician and geophysicist Sydney Chapman, who had developed a theory that the aurora borealis—the northern lights—resulted from electrons that moved through the ionosphere, one of the outer layers of the Earth's atmosphere.

Chapman's theory didn't match observations of the aurora but still became widely accepted. Alfvén, on the other hand, built his work on the back of a series of laboratory experiments in the late 1930s, creating a complex mathematical theory for the behavior of space-based plasma and the aurora. He showed that the northern lights would result from an interaction between the Earth's magnetic field and space-borne electric currents originating at the sun.

Chapman exerted all his influence to block—today we might say "cancel"—Alfvén. Chapman was a fellow of the Royal Society, a member of the U.S. National Academy of Sciences, a scientific advisor at the Geophysical Institute of Alaska, and an honorary fellow of Queen's College, Oxford, Trinity College, Cambridge, and Imperial College, London. Leading journal editors said Alfvén's calculations couldn't be right because they didn't agree with Chapman's.

When the time came for Alfvén to collect his Nobel—in the year that Chapman died—he didn't hold back. Plasma physics, he said in his speech, was "the playground of theoreticians who have never seen a plasma in a laboratory" and "still believe in formulae which we know from laboratory experiments to be wrong." You can almost hear the smile as he apologizes that laboratory plasma "absolutely refuses to obey" the laws other theorists had laid down.

Daniel Shechtman took a similar tone over the objections of his detractors. He won the 2011 Nobel Prize in Chemistry for the discovery of quasicrystals. In his Nobel lecture he mentioned that he had experienced bad reactions to his discovery. Double Nobel

Prizewinners are fiercely driven competitors willing to push the rules to the limit.

laureate Linus Pauling had told him—and everyone else—that quasicrystals couldn't possibly exist, calling Shechtman a "quasi-scientist."

Pauling had what Shechtman calls the "battalions" of the scientists in the American Chemical Society behind him. Even the leader of Shechtman's own research team went along with Pauling, summarily expelling Shechtman. "I was a shame to the group," the laureate recalled during his speech. To the audience's amusement, he showed a powerpoint slide of a black and white cat strutting along in front of a line of glowering German Shepherd dogs. "For a while, this is how I felt," he explained.

When Marshall collected his Nobel Prize, the citation referred to a scientist who "with tenacity and a prepared mind challenged prevailing dogmas." Marshall was a little more explicit. "Before finishing I want to acknowledge all those scientists who failed to recognise [*Helicobacter pylori*]," he said in his acceptance speech. "Without them I would have had a very different career."

Karikó decided to behave herself at the Nobel ceremony: Her speech is a straightforward telling of the story of mRNA vaccine's discovery and development, though she did add that without the sackings she suffered, she would never have taken the path that led to her Nobel Prize. "Focus on what's next," was her only advice if you find yourself in what she diplomatically termed "a situation."

Her restraint may have been due to the fact that she had already celebrated her triumph over adversity at previous award ceremonies. "I'm thankful for people who tried to make my life miserable," she told the audience at the Canada Gairdner International Award ceremony in November 2022. "Those people who demoted me from faculty positions, who fired me from my positions—they made me work harder and improve myself, and without them I wouldn't be here."

Perhaps Karikó originally intended to repeat her comments in Stockholm, but thought better of it in the end. She wouldn't have been the first. McClintock wrote a number of drafts of her speech on notepaper marked with the crest of Stockholm's Grand Hotel, where the laureates always stay before the ceremony. One draft says, "For many years I worked on a genetic phenomenon that was most unacceptable to all but a few persons." She crossed this out. Below it, she wrote that she was "truly amused" by some of her critics: A maize geneticist came to see her once, and said he had heard that she held some strange views, and that he did not want to hear a word about them. "I could not refrain from laughing," she wrote. That story is outlined in almost every draft of the speech, but it didn't make the final cut.

In the end, McClintock contented herself with expressing pleasure at being labeled a troublesome rebel. Because her peers and colleagues ignored and even rejected her, she had been left alone to get on with the work she loved: "I was not invited to give lectures or seminars, except on rare occasions, or to serve on committees or panels, or to perform other scientists' duties. Instead of causing personal difficulties, this long interval proved to be a delight. It allowed complete freedom to continue investigations without interruption." The "old bag," in other words, had it all wrapped up.

MICHAEL BROOKS is a science writer based in Lewes, U.K. His latest book is *The Art of More: How Mathematics Created Civilization*.

The Bacteria That Revolutionized the World

How cyanobacteria killed one climate and created our habitable Earth

BY ELENA KAZAMIA

ILLUSTRATIONS BY MARK BELAN

THERE WERE NO EYES to see it, but the sun shone more dimly in the sky, casting its languid rays on the ground below. A thick methane atmosphere enshrouded the planet. The sea gleamed a metallic green, and where barren rock touched the water, minerals oozed out. Estuaries, creeks, and mud flats teemed with microscopic life—single-celled bacteria and archaea. This wasn't life at its emergence on Earth. This was life on Earth at adolescence, age 1 billion.

Life thrived on the edges, where water met air and air met rock. These organisms carved out a living with metabolisms that drew energy from minerals and gases.[1] But life was a slog. Sulfur and nitrogen, the elements that provided the highest energy currency at the time, were hard to come by, released slowly by weathering rocks. Hydrogen gas, another prized commodity, was voraciously consumed and turned to more methane.

Then along came a rebel, a form of bacteria that discovered a way to live on water and sunlight alone.

Outwardly, little distinguished the mutineer from other single-celled microbes of its time, other than its blue-green color, which eventually gave it its name, cyanobacteria. But on the inside, from the abundant fuels of sunlight and water, cyanobacteria generated more energy than any lifeform before. This new chemical process unleashed a gas that would forever change the trajectory of life on Earth: oxygen.

Today, oxygen feels synonymous with living, but to most organisms inhabiting adolescent Earth, it was lethal. Oxygen is highly reactive—it strips electrons off metals and possessively attaches itself to elements like nitrogen and sulfur, breaking the otherwise stable molecules most microbes had relied on for survival. Inadvertently, the new arrival was making the little food available to microbes inedible. When not reacting with other elements, O_2 is so rapacious it reacts even with itself, releasing free radicals. These fragments of molecules are so unstable they will attack most chemical bonds indiscriminately, wreaking biological havoc. Exposed to high doses of such radicals, all living cells quickly corrode. It's a wonder cyanobacteria survived their own gas. Essentially, they were setting themselves on fire.

The first cyanobacteria might have experimented with oxygen-producing energy only when they ran out of other fuel—a last resort to be used in times of desperation until they gradually evolved the ability to detoxify the oxygen. With Earth's abundance of water and light, cyanobacteria had happened upon an untapped font of energy. Once they landed on a way to oxidize water without self-destruction, a revolution was afoot.

Tiny cells, preserved for 14 percent of the entire universe's lifespan, have been waiting.

That revolution was photosynthesis, harnessing power from light (*phos* in ancient Greek). Cyanobacteria gathered the sun's rays and directed their force to split water particles. Breaking water unleashes a powerful torrent of energy, which the cyanobacteria converted into energy currency, a sugar to store and feast on when needed. The possibilities photosynthesis offered were too numerous compared to the setbacks; there was no putting the genie back in the bottle.

The innovation of photosynthesis also opened the door for other microbes to profit from the energy that cyanobacteria captured from the sun. Without this incendiary reaction, there never would have been enough energy in the food web to produce more complex life, to produce moss or millipedes or house cats or us. And their descendants—modern cyanobacteria, as well as every light-hacking organism on the planet—continue to thrive today, and produce the oxygen we breathe.

PIECING TOGETHER A STORY of organisms that lived 3 billion years ago—that were too small for our eyes to see and that lived on such a radically different world—itself feels a bit like mythmaking. We barely know a fraction of the microbes currently alive on Earth. How can we dare to concoct an origin story for one that lived so long ago?

For centuries, the best and most direct evidence we have had for long-gone organisms has been fossils. And new technology has shrunk down this hunt from giant dinosaur femurs to miniscule microfossils.[2] In her lab at the University of Liège in Belgium, biologist Emmanuelle Javaux uses electron microscopes—and even chemical-tracing—to search for the ancient and seemingly unseeable. The oldest cyanobacteria that have been identified in the fossil record date to the Proterozoic, a period some 1.9 billion years ago. The discovery boggles the mind: tiny cells, just 10 microns long, preserved for 14 percent of the entire universe's lifespan. They have been waiting, in a layer at the top of a microbial mat that had turned into dense crystalline rock. They were, unmistakably, cyanobacteria. "And the way they divide is very similar to some modern cyanobacteria," Javaux says.

In a more recent find, Javaux has dissected cyanobacterial microfossils to reveal intricate structures within their cells—small membranes that present the first "direct evidence of a cell performing oxygenic photosynthesis," she says.[3] The tiny cells in question are 1.75 billion years old. Additional chemical analysis can reveal clues about early cyanobacteria's metabolism and biology. But, for Javaux, "I am always amazed to find such old cells and look at them under the microscope ... they are treasures." Even these incredibly ancient microfossils, however, are roughly 1 billion years too young to reconstruct a proper origin story of the intrepid inventors of photosynthesis.[4]

In the absence of ancestral fossils, other scientists are scrutinizing the genomes of microbes alive today, the living descendants. "Because we're using genes and phylogenies, we can work backward in time earlier than the fossil record," says Greg Fournier, a professor of geobiology at MIT. Identifying pieces of microbial genomes that are the oldest becomes scientists' first step to building a partial profile of the original rebel.

But tracing the evolutionary path backward using only modern cyanobacteria is also difficult. "We don't have direct ancestors," Fournier says. "We have this big, long branch in our tree that separates cyanobacteria from everything else. Along that branch, all of the evolution of oxygenic photosynthesis must have occurred," but the stepping stones are unknown. "Maybe they're out there … but we haven't found them yet," Fournier says. "It's a little bit like trying to understand something about human evolution without any knowledge of the great apes," adds Woodward Fischer, professor of geobiology at Caltech.

Another intriguing way to decipher the history of these planet-changers is to study the environmental signature of their exhales. Because of oxygen's reactive properties, particularly the rusting effect it has on iron, oxygen emissions on a large scale leave a discernible trace in the rock record. A major geological turning point in our planet's history is the "Great Oxidation Event"—or GOE for short—dated to 2.4 billion years ago. It is then that oxygen gas for the first time reached a level of 1 to 5 percent of the atmosphere's composition (still just a gasp from today's 21 percent). Given that much of the initial gas produced would have reacted with other chemicals and been immediately sucked up, scientists conjecture that only sustained cyanobacterial effort could have led to such a dramatic buildup in the planet's atmosphere.

But the first "whiffs of oxygen," prior to the GOE, remain difficult to pinpoint.[5] To search for traces, some scientists are plumbing ancient rocks. Using new methods, one team of scientists, including Timothy Lyons, a professor of biogeochemistry at the University of California, Riverside, asserted that they had detected minute "pulses of oxygen" in the atmosphere, in localized environs, at least some 50 million years prior to the kickoff of the GOE. It is possible that these are either the vestiges of cyanobacterial experimentation, as described by Fournier, or these emissions may have non-biological sources. There are certain geological scenarios where minerals are deformed under mechanical stress and forced to react with water, releasing oxygen.[6]

These might also be parallel narratives converging on a single story: Cyanobacteria first evolved 3 billion years ago, but it took them—and likely an assist from geological processes—another 600 million years to oxidize the planet. "You can divide Earth history in about half," Fischer says, "there's a half without oxygen and a half with oxygen," before and after the GOE—before and after cyanobacteria gained steam with their revolution.

THAT CYANOBACTERIA PREVAILED is astounding not just on the level of each individual organism surviving the toxic assault of oxygen, but also given the catastrophic impacts accumulated oxygen had on the climate. Some scientists have dubbed the GOE the "Great Oxygen Catastrophe." Not only did it poison the air, but it also stripped the atmosphere of its methane blanket. Without this warming mechanism, the globe spiraled into a period of deep glaciation. Temperatures

Today, oxygen feels synonymous with living, but to most organisms then, it was lethal.

plummeted so low, a sheet of ice stretching from the poles to the equator turned the Earth into a giant "snowball." This ice age lasted 85 million years. The survivors eked out an existence perhaps reminiscent of the microbes that live in today's polar ice.

The relentless oxygen levels, a lack of nutrients, and the cold temperatures would have turned most of the places where microbes had thrived for 1 billion years entirely uninhabitable. All from a single spark, a microscopic chemical treachery.

With oxygen ascendent, all of Earth's previous life forms—obligate anaerobes (bacteria and archaea that cannot tolerate even miniscule quantities of O_2)—were forced into refuge in environments free of oxygen. They persist in such refugia today, in stagnant pools, mud pots—like the bubbling acid hot springs at Yellowstone National Park—or near hydrothermal vents deep in the ocean, pockets of the planet that retain echoes of what most of it once was like.

Other organisms got creative, looping in the newly abundant compound for their own benefit. One spinoff was respiration, the metabolic process by which most cells that live exposed to oxygen break sugars to release energy. Respiration is an ancient metabolic invention and likely evolved just after photosynthesis. But respiration can't outpace photosynthesis; to remain a dominant force in the atmosphere, O_2 must be continually produced.

The single, rebellious invention of exploding water to release energy has not been repeated in the 3 billion years of continuous evolution, since cyanobacteria first emerged. Instead, it has passed along the tree of life like a torch of Promethean flame.

The vegetation that populates our Earth, coloring our landscapes green, relies on this ancient alchemy. Instead of inventing their own version, roughly 1.5 billion years ago a bacterium engulfed a cyanobacterium and incorporated its metabolisms whole into its own cellular blueprints—giving rise to an algal cell. This next-level innovation, the enslavement of cyanobacteria, was so profound that oxygen concentrations rose exponentially as algae greened the ocean. It is estimated that today algae produce roughly half of the oxygen on the planet. Fast-forward another billion years, and a portion of these algae gradually evolved into land plants, passing the knowledge of cyanobacterial photosynthesis—nested within its cells—upward along the tree of life.

Cyanobacteria's invention has both the simplicity and depth of a creation story. On the surface, all it brings is the union of sunlight and water to create fuel—and release oxygen. But scientists are still puzzling over the inner workings of today's cyanobacteria. "We still don't know all the tricks that allow them to do this so easily," Fischer says. "You know, the best, fanciest chemists in the building across the quad from

Temperatures plummeted so low it turned the Earth into a giant "snowball."

me, right?" he exclaimed excitedly during our conversation, pointing outside his office window in Caltech, "They would just love to be able to do chemistry so elegantly, in the way that it takes place in cyanobacteria, algae, and plants."

A single organism can, unwittingly, change the atmosphere—and, with it, the entire planet's trajectory. And although it is difficult to conjure, as we live through a climate catastrophe of our own making driven by high levels of CO_2, in the constant, long fluxes of time, there might also be, "a future Earth—millions and billions of years down the line—where CO_2 might be so low that it becomes limiting for oxygenic photosynthesis," Lyons suggests. As our aging sun burns even brighter then, it might snuff all CO_2 out of the air, pushing cyanobacteria and the other photosynthesizers to their twilight. "We're not going to be around to see it—nothing like us is going to be around to see it," Lyons says, but "the world may return to an anaerobic planet. We may return whence we came." And the stage will be set for a new rebel.

ELENA KAZAMIA is a science writer from Greece. She has a master's degree in conservation from University College London and a Ph.D. in plant sciences from the University of Cambridge in the U.K.

REFERENCES

1. Canfield, D.E., Rosing, M.T., & Bjerrum, C. Early anaerobic metabolisms. *Philosophical Transactions of the Royal Society B* **361**, 1819-1836 (2006).

2. Demoulin, C.F., *et al.* Cyanobacteria evolution: Insight from the fossil record. *Free Radical Biology and Medicine* **140**, 206-223 (2019).

3. Demoulin, C.F., Lara, Y.J., Lambion, A., & Javaux, E.J. Oldest thylakoids in fossil cells directly evidence oxygenic photosynthesis. *Nature* **625**, 529-534 (2024).

4. Fournier, G.P., *et al.* The Archean origin of oxygenic photosynthesis and extant cyanobacterial lineages. *Proceedings of the Royal Society B* **288**, 20210675 (2021).

5. Anbar, A.D., *et al.* A whiff of oxygen before the Great Oxidation Event? *Science* **317**, 1903-1906 (2007).

6. He, H., *et al.* A mineral-based origin of Earth's initial hydrogen peroxide and molecular oxygen. *Proceedings of the National Academy of Sciences* **120**, e2221984120 (2023).

THE SHARK LAB AT CALIFORNIA STATE UNIVERSITY

The Shark Whisperer

Donald Nelson spent his life undoing the damage that Jaws *did to the perception of sharks*

BY KATHARINE GAMMON

IN THE 1970S, WHEN A YOUNG FILMMAKER named Steven Spielberg was researching a new movie based on a novel about sharks, he returned to his alma mater, California State University Long Beach. The lab at Cal State Long Beach was one of the first places in the United States to study sharks in a rigorous way. Spielberg was developing a character who was a shark researcher, so he sent an art director to campus. There, the art director found the office of Donald Nelson, the unflappable biologist, spear fisherman, and shark fanatic who founded the lab in 1966. Nelson's office was an art director's dream, filled with maps, scientific papers, shreds of napkins with engineering plans on them, various shark repellents.

The director took every single piece of paper—all the photographs, nautical charts, scribbled notes on napkins—off the wall and made photocopies. Then he put all these pieces back in their places, one by one. He used them to build the character of Matt Hooper, the charismatic double-denim-wearing shark scientist played by Richard Dreyfuss.

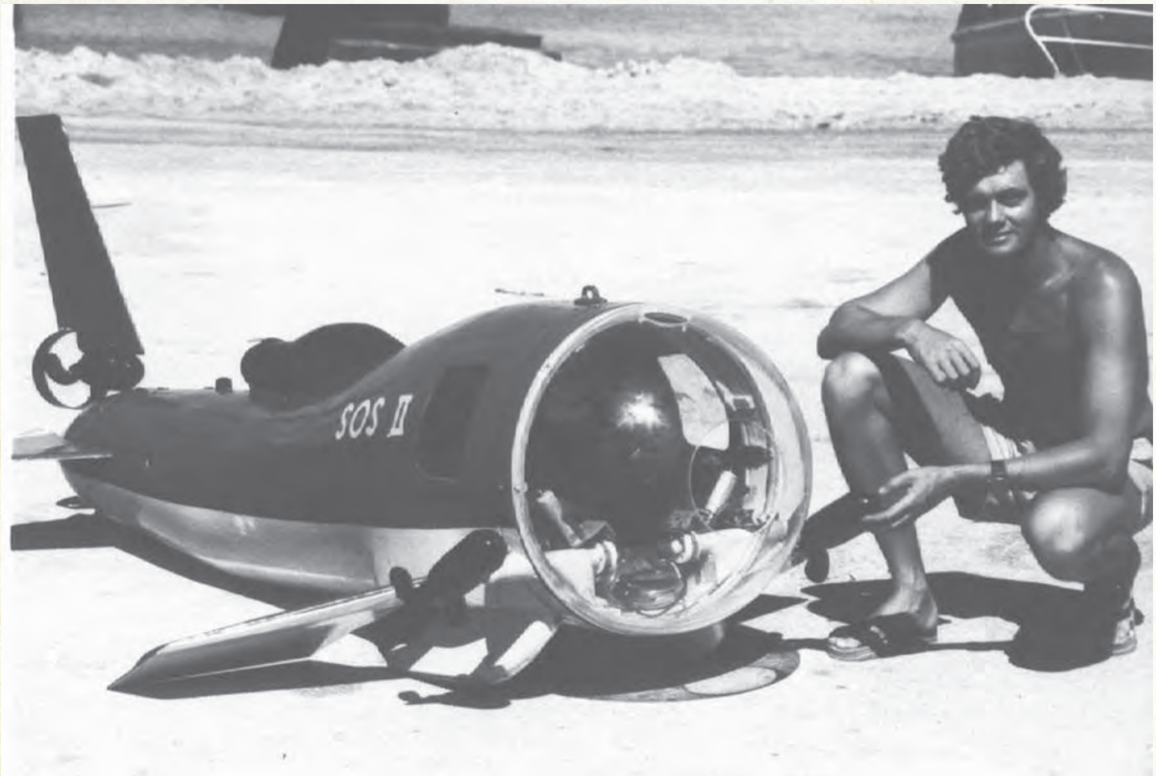
The movie was, of course, a smash hit. It earned over $260 million in its initial domestic release in 1975, enough to make it the biggest moneymaker in Hollywood history to that point. It also left its mark on the reputation of sharks. The opening lines alone, backed by that daggered two-note musical score, gave a sense that sharks were a nearly demonic force: "*It lives to kill. A mindless eating machine. It will attack and devour anything. It is as if God created the devil, and gave it … jaws.*" David Shiffman, a marine biologist and author of *Why Sharks Matter*, says, "*Jaws* made a generation absolutely terrified of sharks."

Nelson was credited as a science advisor and fully supported the film, as well as its 1978 sequel, *Jaws 2*. But over the next two decades, as Nelson's research career took off, he would flip the script about sharks, bringing them out of the dark realm of fevered imagination into the clear light of science. By researching shark behavior up close for the first time, and making countless documentaries that allowed people on their couches into the underwater world he loved, he began to change people's minds. A deadly, despised predator with a face full of teeth began to seem vulnerable, even elegant, a critical choreographer of the ocean ecosystem. By the time Nelson died in 1997, sharks had become the focus of conservation programs across the planet.

NELSON WAS BORN in Plainfield, New Jersey, as an only child, near the eastern shore of New Jersey. He grew up fascinated by fishing, photography, and ornithology—when other kids were playing sports, Nelson was often looking at birds, collecting bird nests, and taking pictures. A lover of cameras and technology, as a child he had a bold ambition to photograph every living species of bird on Earth.

But the ocean tugged at him, and his ability to spearfish meant he could make a nice side income selling fish to restaurants. He got a biology degree at Rutgers University in 1958, and then moved to Florida to study biology at the Marine Laboratory of the University of Miami. It helped that Miami was the spearfishing capital of the United States at the time. Nelson joined a competitive team of spearfishers called the Glug Glugs. Aboard a 22-foot Prowler, he could spend a whole weekend catching grouper—and contributing to his education.

It was on a spear fishing trip in 1959, the story goes, that Nelson met his first shark. He had speared a small grunt—a bottom-dwelling fish known for the guttural noises it makes—and as the fish was making a racket on the seafloor, a shark darted in out of nowhere. "Here



SOS Donald Nelson with the one-person submarine he invented, nicknamed the SOS for Shark Observation Submersible. It would allow him to safely antagonize sharks and record their behavioral responses. The submarine once hung in the Smithsonian Museum in Washington D.C., but is now housed at the Shark Lab at California State University, Long Beach, which he founded.

THE SHARK LAB AT CALIFORNIA STATE UNIVERSITY

was this 4-meter tiger shark looking at Don as if he were a somewhat impaired, large, marine organism—perhaps a strange sea turtle," recalled colleague and former graduate student Samuel Gruber in a eulogy to Nelson published in 2001. No one knew, at the time, whether such a shark might attack on the spot. Don speared it and took it home with him. "That encounter on the reefs in 1959 was both to change Don's life and eventually much of what we know about shark behavior," Gruber writes.

After the encounter, Nelson had an epiphany: Sharks must be attracted to sound. That insight led to one of the first studies of shark senses and behavior in the world. Together, Nelson and Gruber crafted synthetic sounds of struggling fish and recorded them on audio tape. Then they used an ultrasonic underwater speaker developed by the Navy and a tape player and set up field tests with quiet, control periods.

In the initial playback series, a total of 22 sharks came to investigate their phony fish sounds. The sharks only appeared when they were playing the recordings, not when it was quiet. The results suggested that sharks were attracted over potentially long distances to pulsed low-frequency vibrations like those emitted by wounded fish—or thrashing swimmers. Though the duo were still just graduate students at the time and their research had never appeared in a scientific journal before, the findings were published in *Science* in 1963.

Steven Spielberg modeled the Richard Dreyfuss character in *Jaws* on Donald Nelson.

Sharks are notoriously difficult to study. They live in the murk, tend to shy away from divers, and travel constantly. Too large to keep in the lab, and difficult to track in the wild due to their extensive ranges and secretive natures, they weren't the focus of rigorous study until the 1950s. As a result, much of what people knew about sharks derived from brief, spontaneous encounters out at sea—or reports and media coverage of shark attacks.

One attack in particular captured the public's attention. In 1945, a Navy heavy cruiser called the Indianapolis sank between Guam and the Philippines, and sailors were thrown into the sea. Oceanic whitetip sharks were drawn to the scene. Over the course of the next few days, the sharks devoured sailor after sailor. Of the 1,196 men on board, only 318 survived—150 were eaten by sharks. (The event even turns up in *Jaws* as Quint, the shark-obsessed boat captain, is a survivor of the attacks.)

The incident is often cited as the worst shark attack in history, but it wasn't the only attack on Navy crews. Because many naval battles during and after World War II took place in the warm tropical waters of the Pacific Ocean, as well as the temperate waters of the South Atlantic Ocean and Caribbean Sea, and because rescues at sea could often take days in the time before GPS beacons became commonplace, sharks became a significant concern for the Navy. It began funding lab research into the development of methods that could prevent attacks—with little result.

In 1965, Nelson received his Ph.D. in marine biology and was hired at Cal State Long Beach as a professor in the biology department. By that time, his work had a new focus—using his growing knowledge about shark senses to protect people from them. "U.S. military morale was so low that they were having a hard time getting sailors on ships, they were so afraid of shark attacks," says Chris Lowe, current director of the Shark Lab at California State University, Long Beach. Nelson had a grant from the Navy for 17 years.

Nelson and his students wanted to design shark repellents that would deter but not harm sharks. They tried creating shark tasers—cattle prods that shock the shark if it came too close (the problem was, it also shocked the diver). Another project looked at surfactants—soap-like substances—that could be squirted into a shark's mouth. Students would fill fire extinguishers with soapy water of different concentrations and go out into the Catalina channel with blue sharks. "You would hold a mackerel in your hand with one hand, and when the shark could come in you stick this hose in its mouth and give it a squirt," says Lowe. The shark would swim away with his mouth open. "The problem was that 20 minutes later, it would turn around and come back." Nelson's shark repellents never panned out.

THAT NELSON SPENT YEARS trying to develop shark repellents was ironic, because more than any marine biologist, Nelson was dedicated to getting close to sharks, observing them in their natural environments. He was completely at peace in the ocean, calm and unflappable. Nicknamed Reef by his friends, he was said to be more comfortable in the water than out. He would free dive to 60 feet deep and just swim around, peeking into the nooks and crannies of the reef. "He had zero fear of sharks," his widow, Ginger Nelson, told me. "Zero."

An expert free-diver, Nelson swam right up to sharks to observe their behavior. He was famous for what became known as the Kamikaze Technique. "He would simply free dive on a reef shark minding its own business and chase it along the reef face until it became rather trapped," writes Gruber. "At that moment, the shark would either flee or begin the sinister underwater ballet Don called an 'agonistic display.' " The shark would raise its snout, depress its pectoral fins, arch its back, hold its tail sideways, and swim in an exaggerated figure-eight pattern. If he continued to approach, the shark would launch a warp speed attack, lunging forward and then retreating rapidly. Nelson thought this ritualized behavior was motivated by self-defense against a perceived predator, in part because it almost never occurred in feeding contexts and did not seem to be specific to a particular home range.

But after a 1976 brush with a "rather pugnacious" shark, as Nelson called it—he ended up driving it away with his spear—he realized new techniques would be needed to study sharks up close. "With absolutely no engineering background, over dinner with his students, Don got out his pencil and on the back of a napkin, his favorite teaching device, he sketched out a design for a wet, one-man sub," writes Gruber. He called it the SOS: Shark Observation Submersible. A variation of the SOS is still in use today.

THE SHARK LAB AT CALIFORNIA STATE UNIVERSITY

CLOSE AND PERSONAL A diver from the Shark Lab photographs a shark up close. Before Donald Nelson, few researchers studied sharks in their underwater environment. They are wide-ranging, shy away from divers and tend to be most active at night.

Sharks are notoriously difficult to study.

A fiberglass contraption, the SOS allowed Nelson to lie on his belly and look out on the underwater world, controlling it with fins and a small motor. Air tanks meant he could stay below the surface for more time. While he lay there in the submersible's bed, he was multitasking. He would control the direction of his own submersible and film the shark, while another submersible filmed him chasing the animals. "Logistically, it was a nightmare to do," Lowe says. "And dangerous as hell." Occasionally, the batteries would die and he'd sink to the bottom, in need of rescue. Or a shark would bite the propeller off the submersible.

But the SOS had other limitations, too: The amount of time Nelson could spend tracking sharks in it was brief—and it couldn't tell him anything about what they did or where they went under cover of darkness—at night or in the deeper waters of the ocean that the SOS couldn't reach. So Nelson also dreamt up new acoustic transmitter technology that would allow him to track sharks and study them remotely for much longer periods of time. This same technology forms the basis for modern studies of sharks and rays.

"This occurred in the prehistoric era, before integrated circuits, lithium batteries, and well-stocked telemetry vendors," writes Timothy Tricas, a shark researcher at the Florida Institute of Technology and former student of Nelson's, in an essay about Nelson's legacy. "There were even fewer biologists who could tackle the custom electronics designs needed for their research projects. Nevertheless, Don and his students (the present author included) spent countless weekends and holidays designing and soldering together ultrasonic transmitters from discrete transistors, capacitors, and resistors."

Nelson's lab was only the second group in the world to put an acoustic transmitter on a free-ranging shark. Transmitters—either attached to the animal or popped inside a fish that would be fed to them—opened up an entirely new world of remote shark research—following them as they moved over hundreds of miles of open ocean.

OVER 30 YEARS, NELSON'S LAB produced almost 50 publications about shark behavior. His detailed field studies of large free-ranging shark species, such as the gray reef, reef whitetip, blue, angel, leopard, and megamouth sharks, took him to sites all over the world, including the Gulf of California, Marshall Islands, Polynesia, Australia, and the Bahamas. In study after study, Nelson uncovered evidence that sharks are complex and intelligent social animals, rather than the solitary, unpredictable killers driven by primitive instincts and insatiable hunger featured in *Jaws*.

Many shark behaviors are, in fact, extremely predictable, Nelson found. One of the most elegant examples is the agonistic display. But Nelson also found that shark feeding and migratory activity is closely tied to the rising and the setting of the sun: Though it varies somewhat from one species to the next, most sharks travel primarily after dark and feed at dawn and dusk, with some seeming to use the sun as an orientation cue. Nelson and his colleague Richard Johnson studied one species of shark in French Polynesia that is so regular in its daily movements that they were able to forecast where the sharks would appear along an established route within a matter of minutes.

Nelson also found that many sharks are social and capable of learning: In repeated studies of sensory function, he showed they were able to "habituate" to both visual and auditory stimuli and to the presence of humans. And they make friends: A number of species travel in groups, he found, most notably the scalloped hammerhead shark, which forms daytime schools off of several islands and seamounts in the Sea of Cortez. The lemon shark also associates with its own kind, as well as with other species of sharks and rays and certain species of fish, relationships that are mutually beneficial—the shark offers protection to the fish, for example.

Overt aggression, he found, is actually unusual in sharks, outside of the gray reef shark. Few species engage in chasing or threats—either to other sharks or to humans. Even during active feeding, including

Nelson swam right up to sharks to observe their behavior.

infamous "feeding frenzies"—in which multiple sharks vigorously feed together over an extended period in a single area—sharks seem interested only in getting food as opposed to competing with one another. And few species exhibit territorial behavior, Nelson reported in his research.

Observing and describing shark behavior put them in the category of animals that could be understood. Nelson learned to decode their body language and create a dictionary of that language for others. Taken as a whole, his work painted a sympathetic picture of a creature that is like so many other familiar species roaming the Earth: defensive when threatened, social by nature, providing ecosystem benefits to other creatures, driven by the rhythms of the sun and the seasons.

IN OCTOBER 1990, the lab's phone rang. The message: A shark considered to be a living fossil had been caught in a fisherman's gill net off Dana Point, California. The fisherman had brought it in, alive, in the waters off the point.

Nelson was teaching a class, but everyone in the lab knew what to do. They started mobilizing a small army of researchers—armed with transmitters—to meet the shark. Nelson would drive his boat, The Discovery, to Dana Point, while others raced there in cars.

When the researchers arrived, they found a circus of action around the animal. It looked like a hippo's head had been pasted onto an enormous fish body—15 feet long, bronze like a statue, with a wide jaw. Tied by its tail to the boat that caught it, the animal garnered gawkers from both land and sea. Jet skis zoomed in, and a helicopter circled. Some onlookers were shouting about letting the shark—dubbed Mega—go free, while others stripped off their clothes and dove into the cold waters to have the chance to swim with such a rare shark. Only five megamouths had ever been discovered, and they were all dead by the time they were caught. This was the first one caught alive.

A diver with a dart gun implanted two transmitters into the shark that would send back signals about how deep the shark dove and its location.

And then, the rope was untied and the shark disappeared into the waters of southern California. Nelson hadn't made it with his boat yet, but the young graduate students caught a ride aboard a boat owned by Ethan Wayne, son of movie star John Wayne, and Nelson met them at sea and took over the chase.

Over the course of the next three days, the team of biologists tracked the shark aboard the boat, as it zigged and zagged south and west, away from shore, sending back signals to a radio they monitored from the transmitters it carried under its skin. No one had ever seen or recorded a live megamouth before. And now, a boat was following one through its murky underwater habitat for days on end. Some of the graduate students free-dived to see if the megamouth emitted bioluminescence. The feeling on the boat was one of total elation.

"It was like walking on the moon," recalls Jim McKibben, director of the Science Learning Center at Cal State Long Beach, then a grad student in Nelson's lab, "doing something that nobody has ever done before."

NELSON SPENT THOUSANDS OF HOURS filming sharks and collected a massive library of 16-mm film that includes footage of the animals responding to low-frequency sounds and engaging in precisely coordinated behaviors. Between 1968 and 1994, he and his students made 25 documentaries that aired on television or made their way into school classrooms. These shows reached millions of viewers each week, and much of his footage still appears on television today—for

SOCIAL ANIMAL Hammerhead sharks traveling together in a group.

example, Nelson's work featured in the popular 2019 documentary *Deep Blue*, about the largest great white shark ever recorded.

In one of his films from the '90s, *Shark Doctors*, Nelson describes preemptive efforts to protect the white shark, which scientists suspected at the time was endangered, potentially numbering in the low hundreds of individuals, despite a lack of precise population data. "It wouldn't take much to knock that population way down and possibly risk extinction," he tells us, as we witness on screen the gleaming jaws of a white shark clamp down on a piece of bait. Shark fishing, for their meat and fins, was already decimating many species of sharks: They were dying faster than they could reproduce.

By the time Nelson died, an international effort to conserve and protect sharks had begun. It took another decade before major protections could be put in place in the U.S.—two prohibitions of shark finning in U.S. waters were passed in 2000 and 2009. International conservation approaches are still gaining steam.

Today, the shark lab that Nelson founded at Cal State Long Beach spends about half its time on outreach efforts—to educate the beach-going public and lifeguards about sharks off California's coastline—and about half its time on research. Attitudes are dramatically different from what they were in the '70s. "The pendulum has swung from people thinking that sharks are so dangerous and violent, that if you dip your toe in your bathtub a shark is going to eat your whole family—to some people saying sharks are just innocent, adorable, cute puppy dogs that just need hugs and kisses and love," Shiffman says. "We really have the full spectrum now."

Many surfers and swimmers around the world, who continue to suffer rare, isolated attacks, talk about sharks with reverence and respect, describing themselves as visitors in the sharks' homes. In Australia, government officials have done away with the term "attack," instead preferring to use the term "negative encounters"—which they argue is more accurate, as a third of encounters between humans and sharks leave no injuries at all.

Nelson's work somehow straddled both sides of the divide, first helping to stoke fear of attacks through his work in Hollywood, then encouraging us through his research and films to understand sharks as intelligent social creatures, vital partners in the Earth's ecosystem.

In 1995, Nelson found a mole on his left forearm and showed it to his wife Ginger. "He thought it looked suspicious," Ginger recalls. Nelson was fair skinned, had grown up with no sun protection and spent most of his days diving and swimming. So he visited his doctor, who came back with the results: nothing to worry about.

About a year later, the mole returned and Nelson went back to the doctor, who found evidence of stage four melanoma, which had already spread to his lymph nodes, Ginger says. Nelson insisted on continuing to teach and research up to a month before he died in 1997. "He just did not want to give up," Ginger says. "He absolutely loved what he did."

KATHARINE GAMMON is a freelance science writer based in Santa Monica, California, who writes about environment, science, and parenting. You can find her on X (formerly known as Twitter) @kategammon.

Lithium, the Elemental Rebel

What a missing element can teach us about the universe

BY PAUL M. SUTTER

INSIDE EVERY RECHARGEABLE BATTERY—in electric cars and phones and robot vacuums—lurks a cosmic mystery. The lithium that we use to power much of our lives these days is so common as to seem almost prosaic. But this element turns out to be a wild card, a rebel that's been challenging our most basic understanding of the formation of the universe itself.

Beyond the lithium ion-powered batteries, beyond the glass and ceramic manufacture, optical systems, air purification, fireworks and rocket propellants, nuclear weapons, and mood stabilizing pills, lithium is cast about the cosmos. But there is not nearly as much of it out there as there should be. And we don't know why.

JUAN ROBALLO / SHUTTERSTOCK

This wily little element has defied explanation for generations, refusing to obey the rest of our cosmological orthodoxy. The robust Big Bang theory, among other accomplishments, allows us to precisely predict the abundances of all of the light elements across the universe.

There is not nearly as much lithium in the universe as there should be. And we don't know why.

Except lithium.

Which means there might be something wrong with our understanding of the Big Bang. There might be something wrong with our measurements. There might be something wrong with both. Or this might be a signal that there are new, as-yet undiscovered forces that were at work in the early universe. Whatever the solution is, this rebel and its so-called "cosmological lithium problem" are here to teach us a radical new fact about the universe.

We just have to figure it out.

Here on Earth, lithium had laid underfoot since the planet's formation, with nobody suspecting that the element even existed. Taken from the Greek word for "rock," on Earth, lithium is usually only found in trace amounts in larger mineral conglomerations. In 1800, the Brazilian chemist José Bonifácio de Andrada e Silva discovered it as a new ore on the island of Uto, Sweden. Seventeen years later, the chemist Jöns Jakob Berzelius isolated the new element within the ore. Since then, the silvery-white metal has found itself making possible so many of our contemporary luxuries.

But most of the universe's lithium is bound up inside of stars.

Roughly 25 percent of all the lithium in the universe—including lithium in household electronics—originated in the first few minutes of the Big Bang.

The Big Bang theory tells us that 13.77 billion years ago the entire observable cosmos—containing every star and every galaxy in a volume now spanning more than 90 billion light-years across—was compressed into a volume no bigger than a peach.

Mere moments into the Big Bang, the temperatures were so high that all protons and neutrons were melted together into their constituent components, which are tiny particles known as quarks. Any time some quarks got together to make a proton, they just got smashed apart by some violent collision or high-energy radiation. But as the universe expanded, it cooled. At a certain point, somewhere about three minutes into the Big Bang, that exotic plasma cooled to around 1 billion Kelvin—still terrifically hot, but cool enough to allow for the production of stable protons and neutrons.

These nuclear reactions continued, with the newly formed protons and neutrons themselves binding together, creating the four lightest elements on the periodic table: hydrogen, helium, lithium, and beryllium. But after about 10 to 20 minutes of this dance, the expanding universe got too cold to sustain further reactions, locking these elements in place.

It would take until the formation of the first stars, hundreds of millions of years later, for new elements to be fashioned again in the universe.

One of the greatest triumphs of the Big Bang theory is its ability to predict the abundance of these light elements. First calculated by physicist Ralph Alpher in the 1940s using the then-new knowledge of nuclear physics, the work was fully fleshed out in a famous paper he coauthored.

These calculations, collectively known as Big Bang nucleosynthesis, offer one of the most powerful predictions of the Big Bang theory: a precise, on-the-nose estimate of how much of the light elements were made in those first fiery minutes, tested by astronomers through the study of the oldest stars, galaxies, and nebulas in the cosmos.

Except lithium.

These nucleosynthesis calculations predict roughly three times as much lithium as has been observed in old stars (our best proxy for early conditions of the universe). Conversely, in keeping with the element's paradoxical nature, newborn stars tend to have much more lithium than we would expect.

And all of this is only the first quarter of the lithium in the universe. Cosmologists now think the other 75 percent may come from a particular kind of exploding star known as a classical nova. In a classical nova, a white dwarf—the leftover remnant core of a sun-like star—has an orbiting companion. The gravity of the

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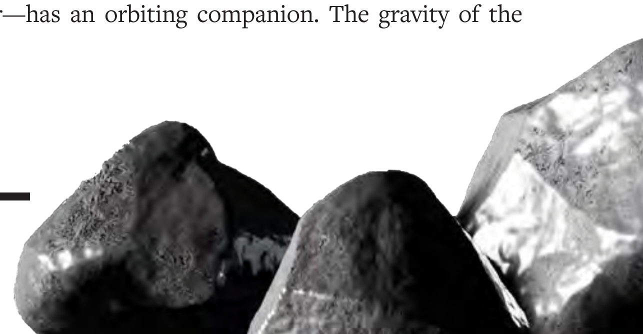
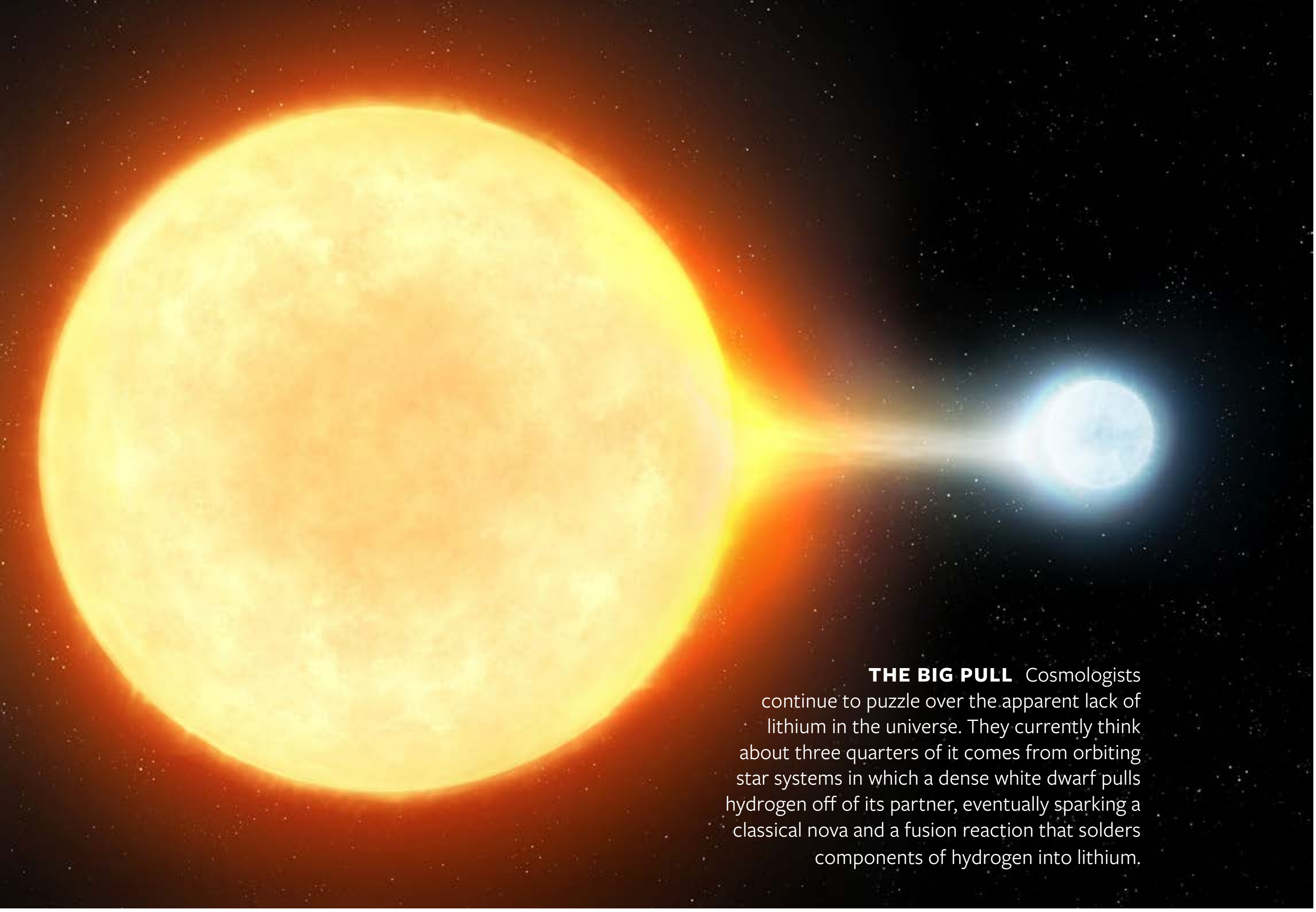




THE BIG PULL Cosmologists continue to puzzle over the apparent lack of lithium in the universe. They currently think about three quarters of it comes from orbiting star systems in which a dense white dwarf pulls hydrogen off of its partner, eventually sparking a classical nova and a fusion reaction that solders components of hydrogen into lithium.

white dwarf vacuums hydrogen gas off of the companion, forming an atmosphere around itself. But when the densities reach a critical trigger point, the hydrogen spontaneously undergoes a runaway fusion reaction, blowing up the atmosphere (and occasionally appearing in our sky as a "new" star—a nova). Because lithium is composed of three protons and some neutrons, the fusion of hydrogen during a nova readily makes lithium in abundance.

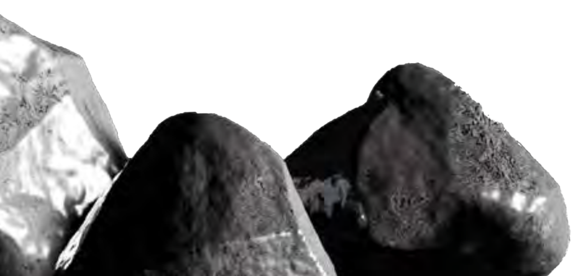
But lithium is also highly unstable, as it has the lowest binding energy of the light elements, meaning that it takes the least amount of energy to tear it apart again. So most of the lithium produced during a nova evaporates into hydrogen and helium. What remains is subject to the ravages of cosmic rays, which can pierce its nuclear heart and destabilize it, vaporizing it in the same way ... or be spontaneously created when a cosmic ray strikes a heavier atom.

Confused? You're not alone. Astronomers cannot figure out which processes play the most important role and what the final tally of lithium should be after all this astrophysical mixing and mashing. All this means that we only have a hazy connection between the lithium produced in the fires of the Big Bang and the lithium that we see scattered across the cosmos today.

When mysteries like this persist through the decades, scientists take it as a sign that the universe is telling them something important. The nature of that important thing is a matter of some debate. And as is usual in physics debates, the theorists blame the observers, and the observers blame the theorists.

One possibility for the strangeness of lithium is that our theoretical understanding of nuclear physics, especially the intense physics operating in the first few minutes of the Big Bang, is not up to par.

NAZARII_NESHCHERENSKYI / SHUTTERSTOCK



Roughly 25 percent of all the lithium in the universe originated in the first few minutes of the Big Bang.

This is difficult to reconcile because, given our mastery of nuclear power plants and nuclear weapons, we seem to have a pretty good handle on these interactions. But there are some intriguing openings. For example, extra-rare reaction chains may contribute to some extra lithium without upsetting the balance of the other elements. Or resonances may play a role. These are special combinations of pressure, temperature, and interaction volume that lead to greater-than-average production of elements. We may have underestimated the importance of some of these resonances in Big Bang physics simply because they don't crop up often in Earthbound experiments.

On the other hand, our observations may be leading us astray. Lithium is a fragile element, so it's difficult to get a handle on primordial populations that have not been touched or contaminated by other processes. The best we can do is search for the oldest existing stars in the galaxy and try to measure the amount of lithium on their surfaces. These old stars are the most likely to be "pure"—to reflect the primordial amounts of lithium manufactured in the Big Bang rather than in later stellar fusion processes. These measurements are less than straightforward, requiring a significant amount of calibration and fine-tuning, because we can only infer the amount of lithium once we know the star's temperature and abundance of other elements. If those calibrations are off, so are our estimates of lithium, giving us only a rough and unrefined picture of how much lithium was kicking around the universe when those stars first formed.

And it turns out that the surfaces of stars might not even be the best place to look for lithium. The vast bulk of every star is made of the two lightest elements, hydrogen and helium. Lithium, being heavier than both, might simply slink into the inner depths of each star, hiding itself from our view. If it sinks too far down, the intense temperatures and pressures may disassociate it, converting it into even more hydrogen and helium.

The most thrilling possibility is that both the theorists and observers are right, but we're completely missing some interesting bit of new physics in the early universe. Perhaps some dark matter, the ever-present mysterious particle that appears to make up most of the matter in the universe, can spontaneously decay into other particles, which messes up the nuclear chain reactions of nucleosynthesis and alters the abundances of lithium. Some physicists have even proposed that the fundamental constants of nature, including the speed of light or the charge on the electron, might have been different in the deep and distant past, which would throw off many of our calculations.

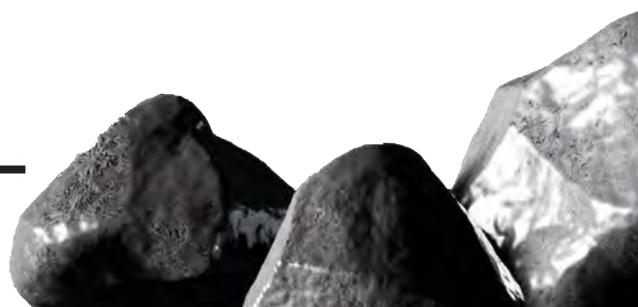
While most astronomers think that the answer is likely in some ho-hum direction like the destruction of lithium in stellar atmospheres, that solution has not been confirmed. We can't crack open stars and see what's going on inside, and so we can't directly test the hypothesis.

Some mysteries lead to vast upheavals of previous norms. Some resolve quietly. But no matter what, rebels can be some of the best teachers, if we are open to them. They force us to reconsider the status quo and realign our perspectives. They act as *agents provocateurs* that guard us from complacency and keep us on our toes. Lithium is doing all that. No scientific theory is perfect, and the Big Bang is no exception. It's only through the corners, the edges, and the gray areas that we have the opportunity to grow and expand our knowledge of the universe.

The Big Bang theory remains today as the dominant paradigm in physical cosmology. It can explain why the universe is expanding. It can explain the existence of ancient relic radiation. And it can explain the composition and arrangement of matter throughout the cosmos.

Except lithium.

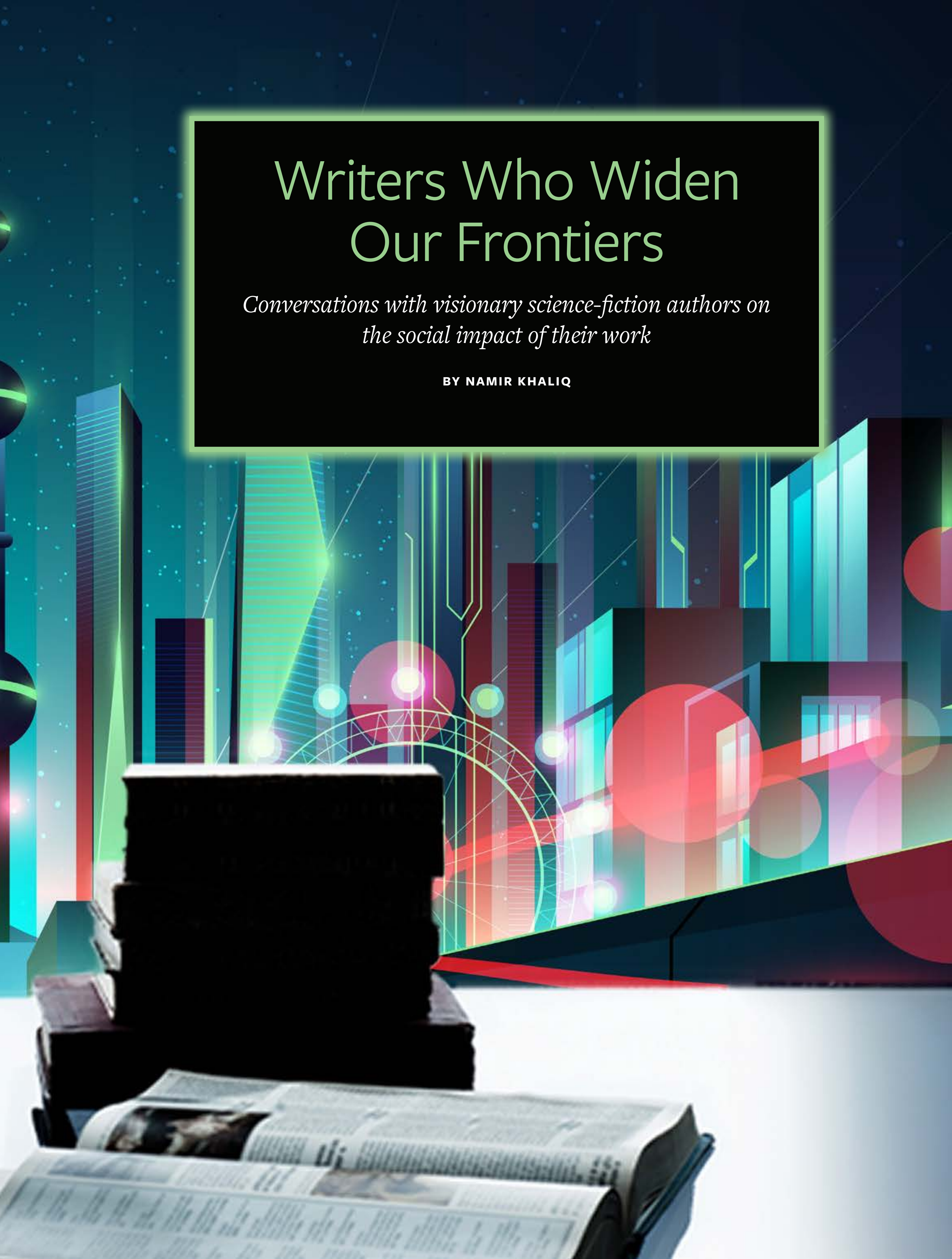
PAUL M. SUTTER is a research professor in astrophysics at the Institute for Advanced Computational Science at Stony Brook University and a guest researcher at the Flatiron Institute in New York City. He is the author of *Your Place in the Universe: Understanding our Big, Messy Existence*.



Writers Who Widen Our Frontiers

Conversations with visionary science-fiction authors on the social impact of their work

BY NAMIR KHALIQ



BEHIND MOST EVERY TECH BILLIONAIRE is a sci-fi novel they read as a teenager. For Bill Gates it was *Stranger in a Strange Land*, the 1960s epic detailing the culture clashes that arise when a Martian visits Earth. Google's Sergey Brin has said it was Neal Stephenson's *Snow Crash*, the cyberpunk classic about hackers and computer viruses set in an Orwellian Los Angeles. Jeff Bezos cites Iain M. Banks' *Culture* series, which unreels in an utopian society of humanoids and artificial intelligences, often orchestrated by "Minds," a powerful AI. Elon Musk named three of SpaceX's landing drones after starships from Banks' books, a tribute to the role they played in turning his eyes to the stars.

Part of this makes sense. Science fiction widens the frontiers of our aspirations. It introduces us to new technologies that could shape the world, and new ideas and political systems that could organize it. It's difficult to be an architect of the future without a pioneer's vision of what that future might look like. For many, science fiction blasts that vision open.

Yet these tech titans seem to skip over the allegories at the heart of their favorite sci-fi books. Musk has tweeted, "If you must know, I am a utopian anarchist of the kind best described by Iain Banks." Yet in Banks' post-scarcity utopia, billionaires and their colossal influence are banished to the most backward corners of the galaxy.

Recently, I interviewed six of today's foremost science-fiction authors. I asked them to weigh in on how much impact they think science fiction has had, or can have, on society and the future.

N.K. JEMISIN is renowned for her groundbreaking works like *The Fifth Season* and *The City We Became*. She crafts narratives that explore themes of power, oppression, and resilience against the backdrop of intricate world-building, earning her global acclaim as a master of speculative fiction.

ANDY WEIR is best known for his debut novel *The Martian*, which was adapted into a hit movie in 2015. Weir's works live firmly in the realm of hard science fiction, fusing meticulous scientific accuracy with gripping storytelling as he explores the ingenuity and resourcefulness of individuals facing extraordinary challenges in space.

LOIS MCMASTER BUJOLD is celebrated for her *Vorkosigan Saga* and having won four Hugo and two Nebula awards. She is a master of character-driven storytelling, weaving together themes of identity and the nature of leadership within richly imagined worlds that blend elements of science fiction and fantasy.

DAVID BRIN is famed for his works like *The Postman* and the *Uplift* series. His narratives often revolve around themes of societal evolution, transparency, and the complexities of human nature, offering insightful examinations of civilizations grappling with technological advancement and their corresponding ethical dilemmas.

CORY DOCTOROW's most recent novels are *The Bezzle* and *The Lost Cause*, the latter of which he describes as "a solarpunk science-fiction novel of hope amidst the climate emergency." Both his novels and acclaimed nonfiction delve into themes of privacy and digital rights, offering provocative insights into the intersection of technology and society.

CHARLES STROSS' notable novels include *Accelerando* and the *Merchant Princes* series. Stross explores the implications of technological singularity, alternate realities, and post-humanism, crafting narratives that deftly blend speculative futurism with political intrigue and social commentary.

PAGES 50-51: TASNUVA ELAHI; WITH IMAGES BY YESDOUBLEYES AND OSTILL IS FRANCK CAMHI / SHUTTERSTOCK

Does science fiction wind up serving as a blueprint for the future we ought to build?

N.K. Jemisin: It shouldn't. Science fiction prides itself on being visionary, but like any literary genre, it just ends up examining whatever issues the author is working through in the present. We just do it more allegorically. If you look back at science fiction from 50 years ago, very few writers land on anything close to our present. Lots of those old books accurately predicted certain technologies, but that was all—they didn't peg how we'd apply them, how we'd break them, how they'd break us. Some of those authors could barely comprehend the idea of women—half of humanity!—as complex beings with their own agendas. Is it a "visionary" prediction of the future when you get one small thing right and flub everything else? Maybe if technology is the only thing you care about. Until pretty recently, science fiction hasn't been very interested in the bigger picture.

Cory Doctorow: There's no denying that a lot of people who actually create things are inspired by science fiction. There's a lot of tangible examples of this. The one everyone cites is the flip phones that were designed by people who were inspired by Gene Roddenberry's props on *Star Trek*. Definitely when we think about space travel, all the stuff that people want to do comes from science fiction. So it's definitely the case that this steers people's vision of it. But don't mistake the analogy for a real thing. It's like people who say what we need to do is all go find Plato's cave. "Why don't we track down that goddamn cave?" And so to treat the allegory as real is to miss the fact that it's an allegory.

Charles Stross: Once you weed out anything that relies on what I call "magic wand technology"—stuff that ignores the laws of physics—you end up with a very limited subset of science fiction that can serve such a purpose. The trouble is, it's more often intended as a horrible cautionary warning than as a desirable destination. The futures depicted in dystopian cyberpunk works such as *Snow Crash* or just plain horrible dystopias like *The Handmaid's Tale* are certainly achievable but absolutely shouldn't be built!

Lois McMaster Bujold: Science fiction does serve as cultural brainstorming, increasing the ambit of the possible. But the fiction part rewards maximizing drama, not sensible, prudent problem solving. These are two different skill sets, not often found in the same persons. So, brainstorming, yes; product development, no. You need Legal, HR, researchers, the shareholders, and the public in on the latter. As they will be financing it all and suffering the consequences of any mistakes.

Beyond inspiring specific technologies, does science fiction ever catalyze real future trends?

David Brin: I've spoken to many who avow that science fiction helped—and helps—them to anticipate the future. Science-fiction notions have inspired positive tech trends from computers to cell phones and many advances in medicine. But it is the mistakes we manage to avoid, sometimes just in time, that qualify some sci-fi tales as world-changers. Retired military officers testify that works like *Doctor Strangelove*, *Fail-Safe*, *On the Beach*, and *War Games* provoked changes and helped prevent accidental war. Citizens know little about how many bad things these protectors have averted. While

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ANDY WEIR

optimism is much harder to dramatize than apocalypse, sci-fi has also encouraged millions to lift their gaze, contemplating how we might get better, incrementally, or else raise grandchildren worthy of the stars.

Andy Weir: I don't believe that fiction should be considered a tool to steer the real world. I write solely to entertain and for no other purpose. I find morals and agendas in stories to be annoying, and they detract from my immersion.

Cory Doctorow: The present is the standing wave, where the past is becoming the future. So if you can change the way people think about the present, you can alter the future. One of the ways to do that is with futuristic allegory. One of the things that science fiction can do that is quite beneficial in terms of how it influences how people think about technology—and this is the thing that cyberpunk did that was so great—is it contests not what the gadget does, but who it does it *for* and who it does it *to*. It becomes a question of the social arrangements of the technology more than the underlying technology itself. One of the great lies of capitalism is Margaret Thatcher's aphorism that there is no alternative. That things have to go a certain way. And at its best, science fiction has people go, "Well, what if we had this gadget that is around us—or that people are predicting will come soon—but it wasn't controlled by the people who insist that it's their destiny to control it?"

N.K. Jemisin: Understanding how society—people—work is key to predicting how the future will develop. That's how you get Ursula Le Guin exploring nonbinary gender in the 1970s, and Octavia Butler predicting America's current slide into Christian nationalist fascism 30 years ago. That's why *Star Trek*'s best episodes were written by people who understood that you can't get to that shiny happy hi-tech future until we change first and prioritize things like making sure everyone eats and gets a decent education. I think this is why some of the best predictive science fiction has been written by writers from marginalized groups, and by anyone else who's had lived experience of society's uglier paradoxes.

Are there times when science fiction is taken too literally?

Lois McMaster Bujold: I want to answer "all the damn time," but that is probably an exaggeration. The thing is that the same is true of all fiction. Writers can only control their words-in-a-row; they can't control how people read them. Each person brings their own experiences, obsessions, traumas, tics, triggers, and limitations to their unique internal construction of what they read, and what comes out the other end of this mental mixer can sometimes have very little relation to what the writer thought they were putting in.

Charles Stross: Yes, the entire current AI bubble is exactly that. The whole idea of AI has been turned into the centerpiece of a secular apocalyptic religion in which we can create superhumanly intelligent slaves that will solve all our knottily human intellectual problems, then work out how to liberate our pure soul-stuff from these clumsy rotting meatbags and upload us into a virtual heaven. And right now, some of the biggest tech companies out there are run by zealots who believe this stuff, even though we have no clear understanding of the mechanisms underlying consciousness. It's an unsupported mass of speculation, but it's threatening to derail efforts to reduce our carbon footprint and mitigate the climate crisis by encouraging vast energy expenditure.

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Some authors could barely comprehend the idea of women as complex beings with their own agendas.

Cory Doctorow: I'd say that virtual reality and cyberspace is the big one. It's a bunch of allegories that are taken for product roadmaps. And the other big one would be AI. These are allegories that are meant to ask us what we mean when we say "consciousness," what we mean when we say "intelligence," what we mean when we create a space for moral consideration of something that's not human, and how the shifting line of moral consideration changes our own relationship to our world—the AI gets turned into a kind of godhead. Then it becomes "let's go make the godhead."

Andy Weir: I think sci-fi has been kind of hijacked by dark, dismal technophobia. Shows like *Black Mirror* are all basically the same thing: "Tech is bad because humanity is bad." But I think it's not true. It's hard to name a technology that has done more harm than good. Humanity is better than people give it credit for.

N.K. Jemisin: A reader's interpretation is rarely just about the text. What the author writes is only half the story, and what the reader brings to that story—their preexisting fears, prejudices, and understanding of the world or lack thereof—is the other half. I do think it's fascinating, however, that quite a few of the works cited by billionaires and technocrats who claim inspiration from sci-fi are cautionary tales ... about what happens if billionaires and technocrats take over.

As the world becomes more secular, could science fiction give people a sense of meaning by imagining these stories as possible futures?

Lois McMaster Bujold: I have said that science fiction's sense-of-wonder is the secular version of the numinous awe sometimes sought in fantasy literature. But really, I think people would do better to look to real science, and the stories it tells, for that wonder in real life. There is no ideology or religion yet devised that cannot or has not been used as a vehicle for humans to be horrible to one another. I don't think just eliminating belief in the supernatural will change that, because the root problem lies in the humans—ultimately, our biology, so perhaps we are back to real science, minus the fiction, after all.

Charles Stross: It already has. There's Russian Cosmism, which started as a Russian Orthodox Christian theologian's weird-ass speculation in the late 19th century before it mutated and infected the global rocketry community. "Space colonization! It's our job to be fruitful, multiply, colonize space, and fill the entire cosmos. And then Silicon Valley!" It follows the same structures as apocalyptic Christianity, except it discarded the inconvenient God/Jesus duo in favor of a spurious belief in its own rationality.

Andy Weir: I think the void has already been filled with other things. Notably environmentalism. I think a desire to believe in something greater than ourselves is inherent in human psychology,

LOIS MCMASTER BUJOLD

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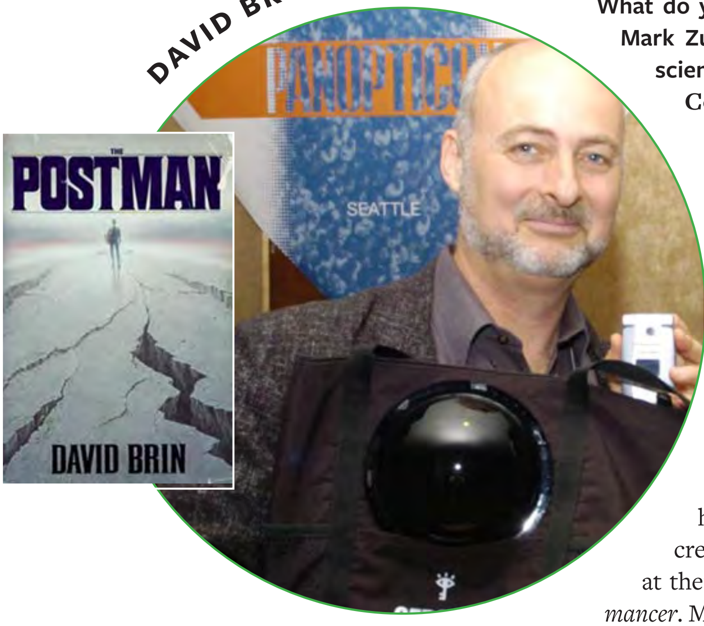
DAVID BRIN



and we're not really capable of going for long without something to look up to. And so we are returning to the place all religions begin: nature worship. That's not to denigrate environmentalism at all, nor am I saying we should ignore the environmental issues we have caused with emissions. I'm just saying that the psychology at play is very similar to religion, and I think it's scratching that itch that people have to be virtuous. It's not so bad for people to feel a moral desire to cut emissions. Just like it wasn't that bad for people to have a religious aversion to murder.

David Brin: Science fiction has already played a major role in the most theologically significant event in history. And it has very little to do with the existence of God. Nearly all prior cultures had mythologies of a Golden Age in the past, when everything and everyone had been much better. Ours is the first major culture to transpose that better world into a possible future that might be built by our descendants. I'm unbothered by the prospect that some of those heirs may be made largely of metal and silicon, breathing hard vacuum as they explore planets and stars on my behalf. What I do care about is doing my job—teaching them, and our regular/organic-style children, too, how to be decent people.

What do you think when you hear Musk, Bezos, or Mark Zuckerberg talk about being influenced by science fiction?

Cory Doctorow: Sometimes I listen to these guys talk and I think, "I don't know what science fiction you read because it doesn't sound like any science fiction I read or write." Which is weird because I think that the first positive review Bezos ever left on Amazon was for my first novel. There's a scene in *A Fish Called Wanda* where Kevin Kline's character keeps misquoting philosophy to his girlfriend, Jamie Lee Curtis, and eventually she turns to him and says, "The central message of Buddhism is not 'every man for himself.' " These people are saying "we finally created the utopia of *Neuromancer*." And I look at them and I go, "I don't think you read *Neuromancer*. Maybe you just played Cyberpunk 2077."

Charles Stross: The thing is, billionaires are not critical readers. They don't seem to have noticed the subtext of the science fiction they read as kids, much less noticed where there's a worrying absence of subtext. Noteworthy exception: Steve Jobs. He's dead now so we can't ask him, but I suspect his vision for the future of computing was, "I want to build the black monolith from *2001: A Space Odyssey*." I can just see teenage Steve getting stoned or dropping acid and seeing *2001* in the cinema and being struck by the vision of a plain black featureless *thing* that reaches inside the ape-men's brains and makes them fundamentally smarter. Every device he produced, from the Macintosh onward, had some aspect of the Monolith to it. The only problem is, Jobs' implementation of the Monolith seems to principally be used to make us angry and stupid, instead of spreading enlightenment.

Andy Weir: I think anything that leads to innovation and funding for research is good. If it's a cult of personality like Musk, or immense wealth on a man-baby like Zuckerberg, it doesn't matter so long as the research gets done. That knowledge remains with humanity long after the people who funded it are gone.

David Brin: Depends on which science-fiction tales influence them. Those who donate to causes—like saving the planet—because they read novels like *Earth* or

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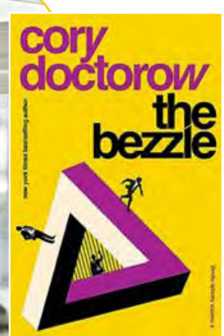
While optimism is harder to dramatize than apocalypse, sci-fi has encouraged millions to lift their gaze.

watched *Soylent Green* may help us avoid dire fates. Alas, some now wallow in prepper fantasies of riding out an apocalypse or "Event" as in some cheap *Mad Max* flick.
N.K. Jemisin: I don't think they're influenced by any science fiction. I think they claim to be because they think it makes them seem smart. Frankly I suspect some of those guys can't read.

Do you ever think that somebody would read your work and go on to build technologies or make decisions that could impact the future of our species?
N.K. Jemisin: No. For one, I don't particularly romanticize technology or accord it more power than it actually has. Tech is a tool. Tools do not have the power to change basic human nature; the person you are with a hammer is the same person you are without it. You want to blame the person that first thought up a hammer for what you do with that hammer? Does that make sense? Language is a tool, too—a more complex one, more powerful, but it does not have the ability to control you. So this whole notion that fiction causes people to do things is just so infantilizing and strange to me. Human beings get exposed to new ideas and tech all the time. Our whole lives, from birth till death, we're adapting to new materials, new methods, new anxieties. How do we adapt/react to those anxieties? That's the choice. That's what matters. Anyone who chooses to destroy democracy or wreck the environment was going to do that anyway. A book didn't "make them do it." You wouldn't buy that excuse from a 3-year-old. They made a choice, then blamed a book in order to dodge or dilute their own accountability. We should probably stop buying that excuse from billionaires, too.
Cory Doctorow: It doesn't matter what you put on the page. There are people who take completely the wrong lesson from it. My first novel is about how horrific reputation economies are and how they produce these winner-take-all economies where you think that you have a meritocracy, but really the people who lucked into a bit of an advantage managed to maintain that advantage over long timescales. And so many people have read that book and sent me well-meaning emails saying, "I read your book and I was so excited. Now I'm going to go and build this technology from your book."
Charles Stross: For the past decade, I've been writing critical political satire disguised as Lovecraftian horror stories. I'm reasonably confident that Cthulhu isn't real, so no risk there! I am, however, regretting the lack of emphasis in *Accelerando* on how terrible the outcome of singularity is for humanity.

CORY DOCTOROW



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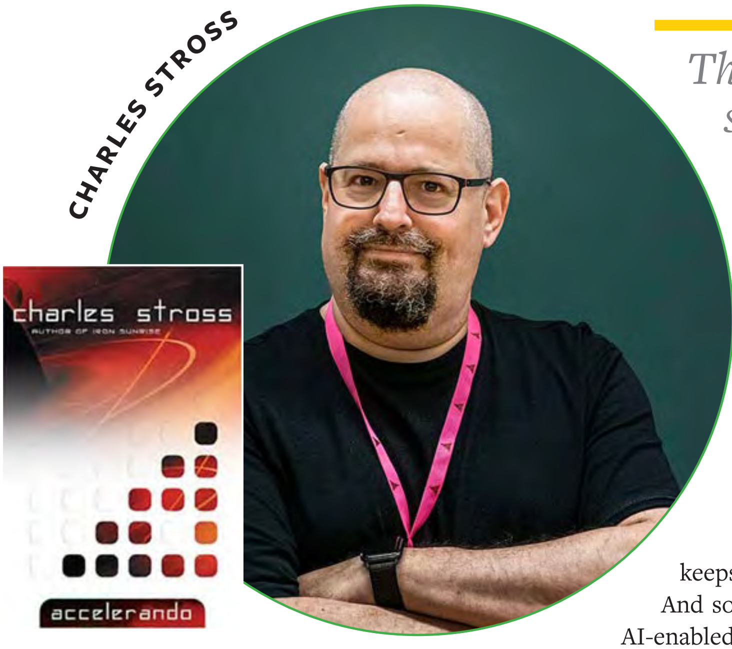
CHARLES STROSS



These people are saying "we finally created the utopia of Neuromancer.*" And I go, "I don't think you read* Neuromancer."

What's the worst technology or idea from science fiction that you're afraid Silicon Valley might turn into a reality?

Charles Stross: Data mining. And it's been here for decades and is getting worse. As an editor of mine put it, "the biggest threat to humanity in the 21st century is too much information." It makes the sort of intrusive police state 20th-century dictatorships wanted almost trivially easy to implement—and the United States is wide open and vulnerable, in the absence of a constitutional-level right to privacy and courts with teeth willing to enforce it in the face of government opposition.

Lois McMaster Bujold: I'm pretty sure Silicon Valley is capable of coming up with all sorts of things I neither want nor need all on their own.

Cory Doctorow: In an era where you can add blockchain to the name of your iced tea company, and increase your share price by $10 million, or add AI to the name of any product, it is all just a way to just make an unfalsifiable claim to being on the cutting edge and having a share in these eventually very large returns that the investor community has assured us are absolutely coming for these technologies. Morgan Stanley keeps saying that AI is a $13 trillion market. And so if AI is a $13 trillion market, then your AI-enabled mascara or fertilizer has some claim on that $13 trillion in value. And so do we need to build AI? And do we need these products to be in a position where they're making decisions at high speed that are incredibly consequential for actual human beings? Absolutely not.

David Brin: There are many clichés about AI, like Skynet or The Blob. If these geniuses in the Valley make new entities that are super smart feudal lords or despots of unaccountable blobs, then we might be screwed. But if these new beings have boundaries, individual differences, and some rivalry, then we might use incentives to get some of them to protect us from the worst of them. Isn't that already what we do with supersmart, predatory entities called lawyers?

Do you see science fiction's influence on Silicon Valley and its leadership as a net positive, net negative, or entirely negligible?

Cory Doctorow: It's neither negligible nor is it measurable in a way that would allow you to make an easy characterization of net negative or net positive. I think that it's very hard to extract the meaning of and the significance of science fiction to technology without also thinking about the relationship of technology to science fiction, right? A lot of the science fiction was written by people who worked in tech and were really

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The whole idea of AI has been turned into the centerpiece of a secular apocalyptic religion.

excited about it. Personal computers and modems are absolutely coterminal with me going to the science-fiction bookstore in downtown Toronto and buying everything on their 25-cent rack and reading it all. Those two things are influencing people at the same time. So I think it's a mistake to think, "Oh, well, science fiction is the literary inspiration for technology" without understanding that technology is the inspiration for science fiction as well.

Charles Stross: I think that at this point, Silicon Valley's culture is self-selecting for people who are compatible with the world view it embodies. It grew out of an industrial revolution initially driven by engineers—and mainly appeals to white STEM-educated males who have been trained to view themselves as the intellectual elite and to believe that all human problems can be solved by the correct application of technology, which is itself the buried theme of Gernsbackian science fiction from the 1900s. The damage is already done.

Can science fiction sway the direction of society?

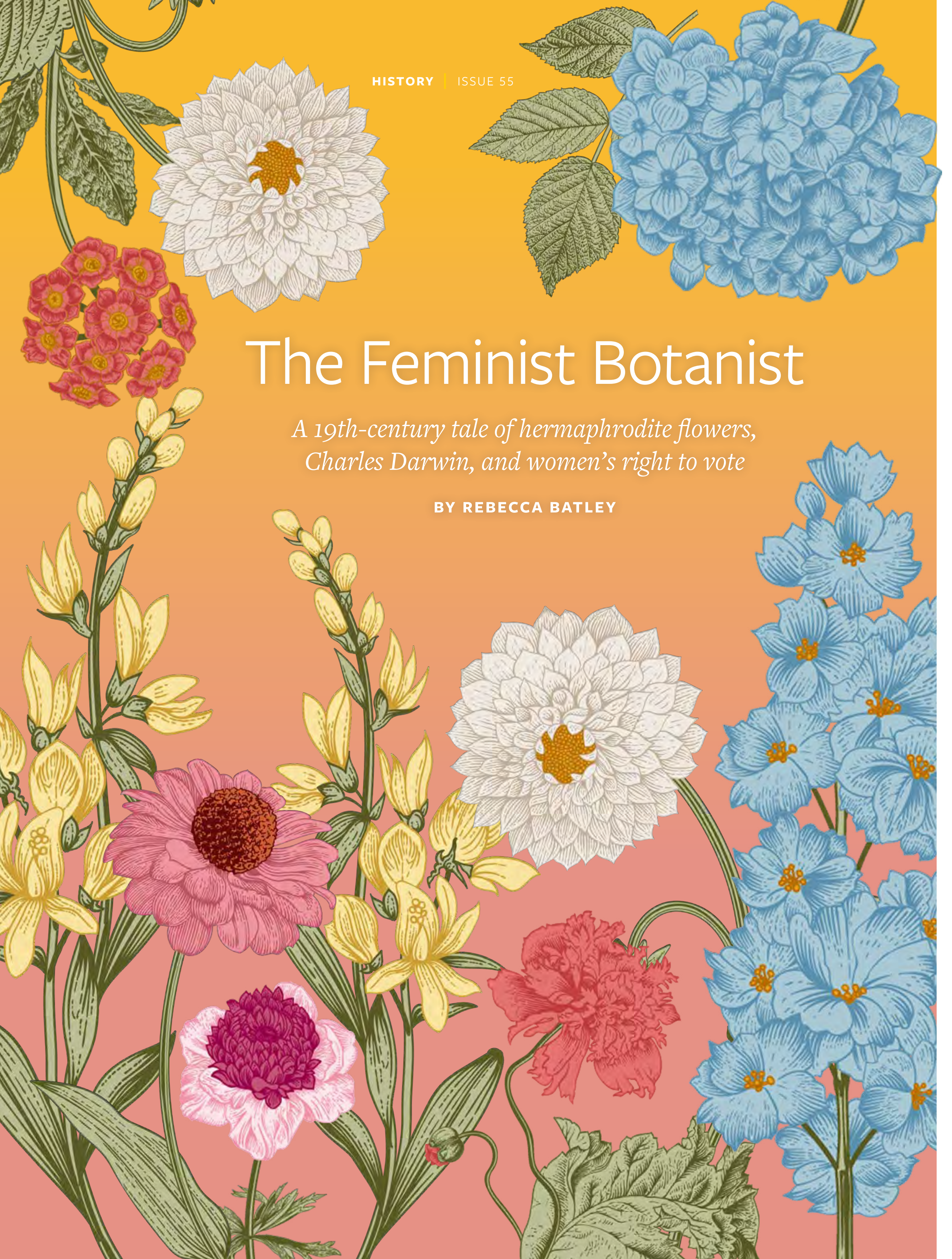
Andy Weir: Honestly? No. We're entertainers. When writers forget that's their main job, their work suffers. No one likes to be preached at. If I can inspire some kids of today to be the scientists of tomorrow, then great. But I don't think there's any specific ideas I've had that would lead to a scientific breakthrough. I think there's a very good chance that my profession is going to vanish in my lifetime. If not mine then in my son's because, how long will it be before an AI can just read a million books, find out what people like about them and what they don't, and then be able to make a story?

David Brin: We should be treated as the sage visionaries that we are! Seriously, we've been at this warning biz for a long time. The last 100 years of sci-fi is a trove that should be remembered and tapped, whenever anything really strange looms on the horizon; it's likely some crackpot wrote about something like it in the past.

Lois McMaster Bujold: Brainstorming is science fiction's proper job. Winnowing the results is a different and weightier task. People don't, in general, die from reading a bad novel, which is why writing can be one of the most unregulated professions in the world. You can spot the professions that can kill people by all the tests, certifications, and laws that hedge them—engineering, medicine, piloting both air and water, even accounting and law itself. Do not get these two categories mixed up.

Cory Doctorow: Have you met science fiction writers? I mean, they are completely daffy about technology half the time. I don't have any grip on technology.

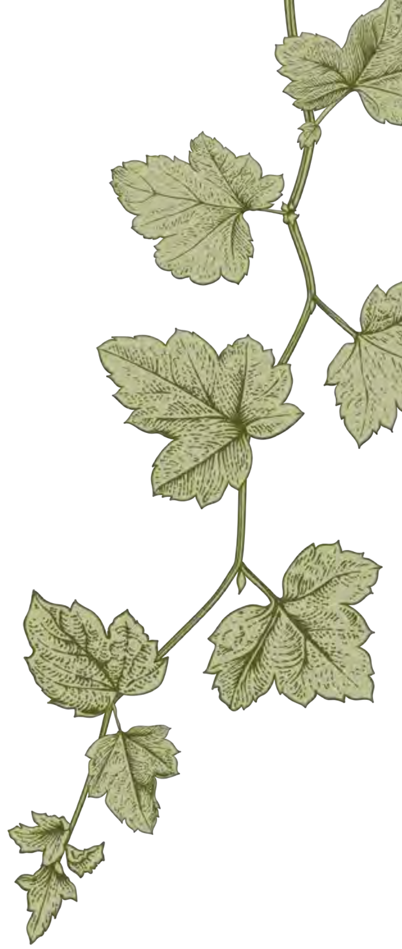
NAMIR KHALIQ is a film producer and the founder of Protostellar Media, a science communication production company.



The Feminist Botanist

A 19th-century tale of hermaphrodite flowers, Charles Darwin, and women's right to vote

BY REBECCA BATLEY



LYDIA BECKER SAT DOWN at her desk in the British village of Altham, a view of fields unfurling outside of her window. Surrounded by her notes and papers, the 36-year-old carefully wrote a short letter to the most eminent and controversial scientist of the day, Charles Darwin.

It was May 18, 1863, and on a thin piece of paper, she humbly presented herself in a clear sloping hand and enclosed local flowers she had been examining, *Lychnis dioica*. These were not just any country lane blossoms, their vivid magenta petals common enough. With her keen eye, Becker had noticed something unusual about their reproductive bits that would challenge the very conception of the sexes in botany—and beyond.

Down in London, Charles Darwin, inundated with letters, may have nearly missed the missive, but he did open it. It was not the first time he had been sent botanical samples by a stranger, but in this note, three unexpected words jumped out at him: “unique ... bisexual flowers.”

Darwin scarcely had time to examine them before Becker headed back out into the wooded grasslands near to her house. She wished to gather and share more botanical samples, feeling that her first letter perhaps didn’t make her point sufficiently. To this end, Becker boxed up a small package of further evidence in the form of samples of this curious plant, its seeds, and pollen—and described to Darwin in detail her wild idea that this plant could transcend reproductive norms. It could fill the roles previously prescribed separately to male and female individuals. Becker was more confident in this second letter, sent just three days after her first, sure now that she had observed botanical sexual variations that were both unique and would be of use to Darwin. She was right.

Prevailing scientific theory at the time maintained that plants had been created as intended by God—and that plant reproduction echoed other sex patterns established in the Bible: There were male and female plants, which together could create new life. Darwin was challenging these ideas. His 1859 *On the Origin of Species* had, just four years prior, suggested that all plants had evolved from four or five progenitors and that the evolution of reproduction within plants had occurred incrementally as resources and tasks had evolved—being shared by both sexes.

OLGA KORNEEVA / SHUTTERSTOCK

BOUNDARY BREAKER
In the mid-19th century, Lydia Becker began collecting botanical examples of plants that blurred the lines of the previously established sexes. She would later advocate for more equity between the human sexes.

ARTUK / WIKIMEDIA COMMONS

When Becker wrote to him, Darwin's botanical studies were focusing in on the nature of plant reproduction, and he was in the process of gathering samples from all over the British Isles. His findings were leading him to argue that plants had evolved in the same manner as animals—and that their reproductive system and evolution was much more complex than the simple binary gender system that had been promoted since the 1730s through the widely accepted Linnaean categories.

Darwin argued that, unlike Adam and Eve, plants were not subject to strict male and female roles. Instead, he suggested, their reproduction was driven by natural selection mechanisms which promoted cross-pollination and that within individual plants, the male and female sexual systems could in fact be combined or merged. This idea dared to blur the strict male-female binary system accepted by Victorian society—which horrified his critics, who attacked him for flagrant immorality. Critics such as theologian John Leifchild accused him of "excluding (the) Deity from acts of creation" and implying that Adam and Eve were no more than fictional characters in a story.

Today, we know that most plants are, in fact, hermaphrodites, able to self-fertilize, and can reproduce sexually, asexually, or by both methods when necessary. (Although most plants seem to avoid self-fertilizing if possible, to avoid the dangers of genetic inbreeding.) Only 5 percent of all plants, it turns out, have fully separate sexes. Hermaphrodites benefit from being able to self-fertilize, and thus survive when no suitable mating partner is available. Darwin was just beginning to grasp this when he was trying to untangle the evidence and work out why botanical hermaphroditism would ever be inferior to the established idea of fully separate sexes.

Enter Becker, who joined a growing legion of scientists who read Darwin's work and were flocking to this provocative revolution.

Three words jumped out at Darwin: “unique ... bisexual flowers.”

In keeping with convention for privileged young women, Becker had been educated at home, with the exception of a few months spent at boarding school. Early on, she was fascinated by the sciences, especially botany and astronomy, interests in which an uncle—though not her parents—enthusiastically encouraged her. As she got older, she grew increasingly frustrated by the restrictions contemporary society placed upon her life and her intellectual development as a woman.

Chafing against the expectations of her to assume the métiers of wife and mother, Becker instead turned her attention to developing her own intellect (particularly in studying the science behind the sexes) and helping other women do the same. To this end, she founded the benign-sounding Manchester Ladies Literary Society in 1865. Social book club, it was not. It was a serious scientific organization through which women studied and shared their research and findings. Becker passionately believed that, “It is better that maids, old and young, should graduate in the School for Science rather than in the School for Scandal.”

And from this position she never wavered. Becker never married, preferring to believe in a more natural and—to contemporary Victorian eyes—radical alternative and sexual social order in which women were not inferior and subject to men.

Becker continued to live in her family home with her relatives and study the flora in and around the countryside surrounding Manchester, walking the parks frequently, scanning the ground for the unusual or perfect specimen, which she would carry carefully home to examine more closely. Becker kept up with the most current literature in the discipline. A steady stream of publications on the science of more exotic plant specimens, sent by other scientists and those which Becker ordered, fell through her letter box with a frequency which raised the eyebrows of her family.

By 1863, Becker felt confident enough to publish what she termed her “own little book” called *Botany for Novices*. In what appeared to be an unassuming overview, she set out basic botanical principles, featured her favorite plants—“I love the English Yew with its thousand years of gloom!”—and daringly discussed her growing interest in plant sexuality and hermaphroditism.

It was this interest that led Becker to approach Darwin. She had observed that some plants did not follow the sex-defined roles that she saw enforced on humans by British society. If plants could deviate

ALL-IN-ONE
The *Lychnis dioica*, also known as *Silene dioica* or red campion, like some 95 percent of flowering plants, does not come in strictly male or female forms.

from these presumed patterns, could people? Perhaps she could use her observations of sexes in the natural world to argue for gender equality in the socially constructed one.

In her first letters to Darwin, Becker asserted that she had found male, female, and hermaphrodite specimens of the *Lychnis* flowers around Manchester. She proposed that the hermaphroditism was an adaptation to its Manchester environment, maybe as a result of the increased urbanization or the harsher climate. Darwin had similar thoughts at the time, and Becker's observations supported his ideas about situational botanical reproductive adaptations. Darwin wanted to see if he could replicate what she had found. He sowed the seeds Becker had sent him. He followed her methodology in order to, "try, as you have done, next year to fertilize the little ovaria." He would later refer to Becker's observations in his own published works on the subject.

Encouraged by Darwin's interest, Becker sent him a copy of her own book. In return, he sent her a copy of his own papers "Two forms in species of *Linum*," which detailed his view on flax's reciprocal sexual relationships and hermaphroditic forms.

Soon letters between Darwin and Becker were winding their way back and forth, up and down the Great North Road. Between 1863 and 1869 Becker's letters become more informal and bolder; she tells him that her Manchester Ladies "society appears likely to prosper beyond my expectations" and that she transcribed his letters without permission—but feels sure he will not object.

Powered by the success of her scientific society, by 1866 Becker turned her attention to what she felt were more pressing matters. She wrote once again to Darwin, this time telling him that she "had not been able to pursue my study of the *Lychnis* flowers nor my endeavour to penetrate the mystery of their variation of form, for since then we have ceased to reside in the country and now [I am] surrounded by acres of bricks and mortar." The family had moved into burgeoning, urban Manchester. This move away from the flora-filled lanes and fields, however, gave Becker the opportunity to share her knowledge with those among whom she now lived. Manchester was then a hotspot

ESA YLISUVANTO / SHUTTERSTOCK

The idea blurred the strict male-female binary system accepted by Victorian society—and horrified critics.

of social foment, where the issues of women's rights, racial equality, and workers unions all were bubbling away. And she formed a new group in its midst, which proved wildly popular.

Eager to provide for the group worthy educational material, not just material deemed suitable for women, she wrote to Darwin and asked him to send her a paper for her to read aloud at the first meeting of her new society. Darwin dutifully sent her the requested papers.

Whether or not he knew he was writing to a feminist society is unclear, but the fact that Becker wrote to him on paper clearly headed "The Manchester National Society for Women's Suffrage" made her position quite clear. Becker's scientific studies had by now helped to bolster her view that there should be equality between the sexes, and that although the sexes had differences in the natural world, there was no evidence that one form was superior to the other.

Her research on the roles of the sexes came to the attention of Manchester's Medical Officer for Health, who used her work as the basis of his argument for equal access to healthcare between the sexes in the new health system the city was founding. Becker was soon taking to the meeting halls of Manchester and giving talks on such contentious subjects as the role and legal position of wives, the right of women to education, and the right of women to vote. She toured the north of England, lecturing on scientific and feminist topics. In November 1867, she escorted Lily Maxwell to the polling station in Manchester to cast the first parliamentary vote by a woman in the United Kingdom since women had been disenfranchised 35 years earlier.

Becker continued her scientific studies, asking the advice of Darwin on various botanical matters until 1870. In her last surviving letter to Darwin, she offers her own position regarding his theory of Pangenesis—one of Darwin's later (and eventually disproven) theories about heredity in which he suggested that cells were cast off around the body and accumulated in the sex organs for reproduction. In her letter, she clearly has reasons for doubts about this idea—and expects Darwin himself will be interested in hearing them.

Most of Darwin's responses to Becker have been lost. But it's possible he, too, eventually came around to the idea that, as Becker concluded, if no plant sex was superior to the other, then surely the idea that, as she wrote, "man has superiority or headship over woman [is] the root of all social evils."

REBECCA BATLEY is a historian and writer, specializing in women's history. She has worked for, among others, the Museum of London and Wessex Archaeology. Her work has appeared in numerous publications all over the world.

The End of Species

Why it's time for new ways of naming life

BY JASON ROBERTS

W**HEN HE CAN SPARE** the time, Jan Mees is an exorcist of scientific ghosts.

A marine biologist, Mees's full-time job is directing the Flanders Marine Institute in Ostend, Belgium, but his side project is serving as co-leader of an international group of volunteer scientists. Together, they're working to build a World Register of Marine Species, a comprehensive database vetting the accuracy of scientific names for aquatic life. It was a daunting task from the beginning, but Mees and his colleagues have been surprised by how much of their work involves not adding to the register but subtracting from it.

After analyzing 418,850 species, the project has eliminated 190,400 of them—more than 45 percent—as redundant. The species *felis* and *Triakis semifasciata*, for instance, are in fact both the leopard shark. *Octopus rooseveltii*, named in 1941 as a tribute to then-president Franklin Delano Roosevelt, already existed as *Octopus oculifer*, named in 1909. No one knows how many previous generations of marine biologists devoted their careers to studying a notional species, not realizing that their peers were studying it under different names.

One of the most prolific over-classifiers, they've discovered, was 19th-century biologist Louis Agassiz, who eagerly declared and named North American species based on little evidence, and even less scientific rigor.

Viewing a single sample of fossilized teeth, Agassiz determined they defined not three different species but three completely new genera of fish. They've since been matched to teeth belonging to the fossil of a single individual fish, collapsing an entire branch of his imagined taxonomy. Hundreds of Agassiz's species identifications have been abandoned on similar grounds.

CREATIVEANGELA / SHUTTERSTOCK

Presently, the greatest single instance of systematist ephemerality is the case of *Litteronia saxatilis*, a shore-dwelling sea snail commonly known in English as the rough periwinkle. Easily found on beaches on both sides of the North Atlantic, the rough periwinkle long ago developed the ability to blend into its immediate marine environment by varying the size, the coloration, and even the shape of its shell.

The mollusk inside the shell is unchanged, but two centuries of classifiers, not only focusing on external morphology but accepting empty shells as definitive type specimens, made the rough periwinkle the "champion of taxonomic redundancy," according to Mees. Since its initial naming in 1792, *Litteronia saxatilis* has been identified, named, and cataloged as a separate species or subspecies no fewer than 112 times. The World Registry of Marine Species has quietly erased those identifications, retroactively updated the scientific literature to point to the original designation, and moved on.

Why so many duplications?

Most are products of the Linnean emphasis on appearance, which allowed minor physical variations to be interpreted as novel species. Some constitute genuinely separate discoveries, obscured by the difficulty of reviewing printed scientific literature in the days before digitization and database searches. Still more are the results of overzealous imaginations, seeking a measure of immortality by declaring a "discovery" where none existed.

To estimate how many officially designated species are mistakes or duplicates, on land as well as underwater, John Alroy, a paleobiologist at Macquarie University in Sydney, Australia, has devised a "flux ratio," a predictive metric extrapolated from the number of corrections already made to taxonomic data. Alroy's flux ratio predicts that ultimately, 24 to 31 percent of all current species names will eventually be discarded as redundant.

We've also been subject to a different kind of illusion: seeing one species where in fact there are several.

One of the more surprising results of genomic analysis is the discovery in 2021 that the giraffe, believed to be a single species since Linnaeus named it *Giraffa camelopardelis* in 1758, is in fact four distinct species, genetically distinct for at least a million years. This

DIVISIVE Eighteenth-century biologist Carl Linnaeus is credited with developing the modern system of taxonomy by which science has named and categorized species ever since. But now, some scientists are calling for a new approach to understanding life on Earth.

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Ultimately, 24 to 31 percent of all current species names will eventually be discarded as redundant.

startled zoologists, who are now rushing to reevaluate everything thought to be known about what seemed a familiar animal. "To put our results into perspective, the genetic differences between the distinct giraffe species are similar to those between polar and brown bears," says Axel Janke, a geneticist at Goethe University in Frankfurt, Germany. "We've clearly completely forgotten what a giraffe is."

The finding has also galvanized conservationists. As a single species, giraffes were already classified as "vulnerable" on the International Union for Conservation of Nature's list of threatened species. Now understood as separate species and therefore separate populations, at least three of the four meet the criteria for reclassification as "endangered" or "critically endangered."

As we've come to realize, species exist in mind-boggling numbers. Even with the elimination of duplicated or imaginary species, we're forced to confront the fact that we've barely begun the tally of life's diversity. As advances in genetics now make clear, the number of extant species—as defined by genetically distinct reproductive populations—is vastly greater than previously imagined.

How much greater?

That number keeps revising upward. In 2011, the most exhaustive survey of biodiversity yet undertaken came up with an estimate of 8.7 million species, of which only 1.2 million had been cataloged thus far. That estimate meant that 86 percent of all land-dwelling species, and 91 percent of all aquatic species, remained undiscovered.

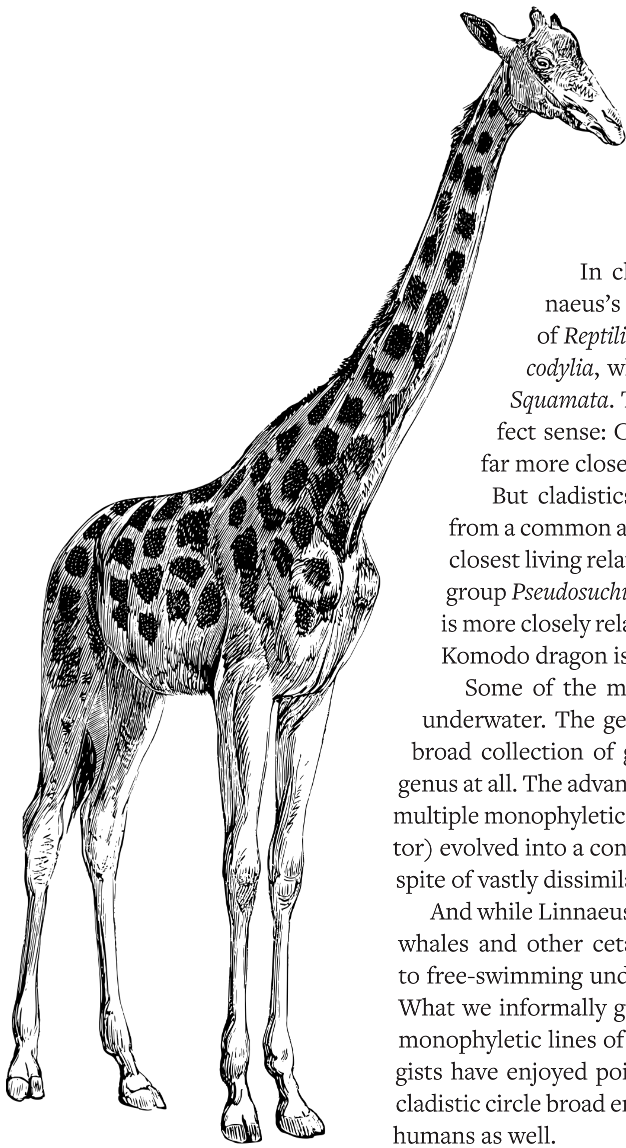
Yet those numbers were dwarfed by a preliminary report five years later from the National Science Foundation. An NSF project called Dimensions of Biodiversity is using gene sequencing to identify species down to the microbial scale, and while it will take years for full results to emerge, project members already estimate the total number on Earth is more than 20 orders of magnitude greater than previously understood.

"Until now, we haven't known whether aspects of biodiversity scale with something as simple as the abundance of organisms," reports Kenneth J. Locey, a postdoctorate fellow at Indiana University and a Dimensions of Biodiversity researcher. "As it turns out, the relationships are not only simple but powerful, resulting in the estimate of upward of 1 trillion species."

One trillion species. That would mean we've discovered and recorded only 1,000th of 1 percent of all possible entries in a catalog of life.

WHILE GENOME-SEQUENCING TECHNOLOGY gets faster and cheaper each year, it also produces cladistic connections that strain our ability to grasp at the larger whole.

The giraffe, believed to be a single species since 1758, is in fact four distinct species.



In classical taxonomy, birds presently remain in Linnaeus's original class of *Aves*. In the separate Linnean class of *Reptilia*, alligators and crocodiles belong to the order *Crocodylia*, while lizards and snakes currently occupy the order *Squamata*. To a mindset based on morphology, this makes perfect sense: Crocodiles, lizards, and snakes resemble each other far more closely than any of them resemble birds.

But cladistics traces monophyletic evolution—that is, descent from a common ancestor. Despite their appearance, *Crocodylia* are the closest living relatives of *Aves*, both having emerged from the cladistic group *Pseudosuchia* around a quarter of a billion years ago. An alligator is more closely related to a peacock than it is to a Komodo dragon. That Komodo dragon is more closely related to you.

Some of the most disorienting results of cladistic taxonomy are underwater. The genus of *Cancer*, or crab, is now understood to be a broad collection of genetically distant species—in other words, not a genus at all. The advantages of developing a crablike anatomy are such that multiple monophyletic lines (organisms descending from a common ancestor) evolved into a convergent body shape, creating close resemblances in spite of vastly dissimilar origins.

And while Linnaeus ultimately recast the class *Pisces*, or fish, to exclude whales and other cetaceans, so many evolutionary paths have adapted to free-swimming undersea life that *Pisces* has now been retired entirely. What we informally group as *fish* represent more than a dozen different monophyletic lines of descent, so genetically diverse that, as some biologists have enjoyed pointing out, "fish" do not really exist. If one drew a cladistic circle broad enough to encompass all fish, the circle would include humans as well.

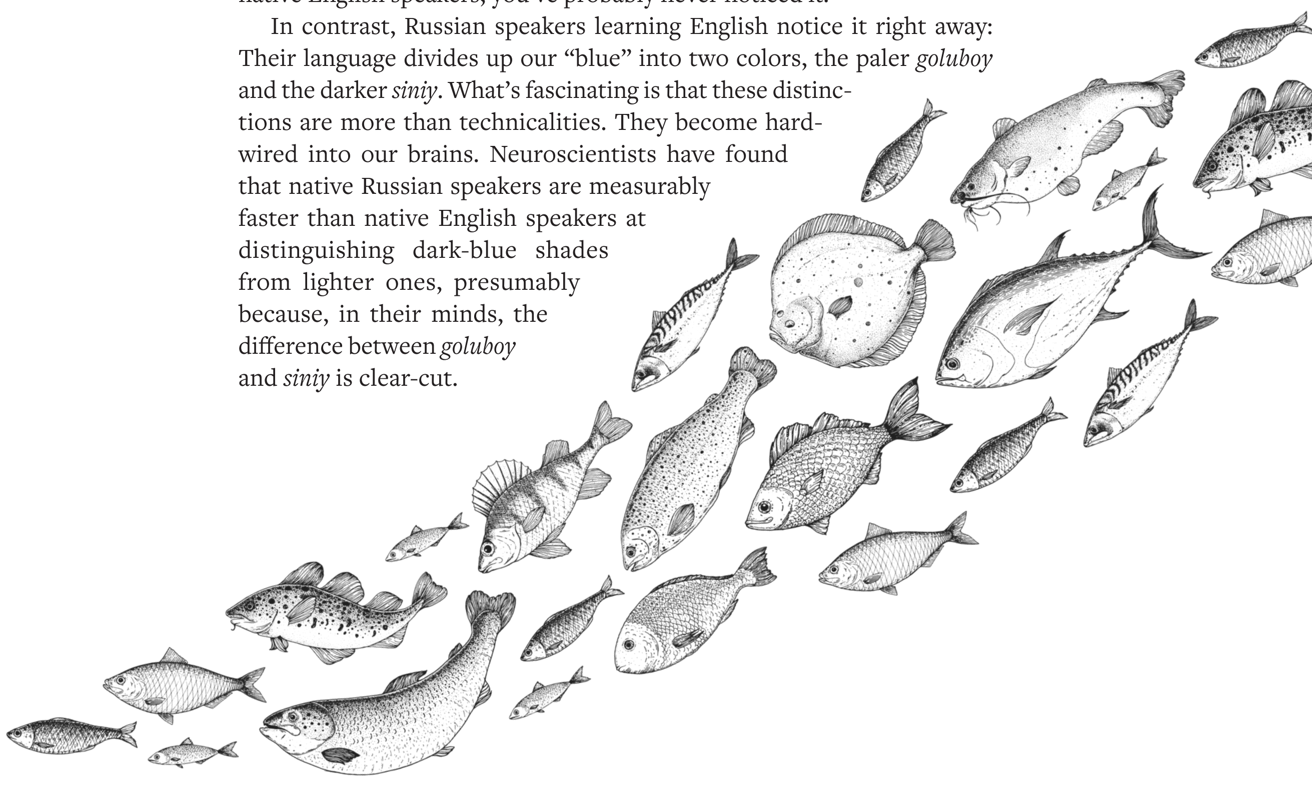
YET HUMANS NEED "FISH," or something very like the concept of "fish," to make sense of the world.

Words are not just units of speech; they are units of thought. The decisions we make in organizing the world tend to disappear once we've made them, but they're inevitably encoded in language.

Take colors, for instance. Among English-speaking people, we distinguish pink as a separate color from red. In the Malaysian language (Bahasa Malay), however, there is no pink. There is only *merah*, red. You can try to approximate a concept of pink by describing it as "light red," but even then you'd be imprecise: The closest term in everyday use is *merah muda*, which means literally "young red," and which can designate a bright red as well as a light one. You can convey the sense of pink by evoking a pink object, such as *merah jambu*, or "red like a guava." The only problem is that you're now describing not a range of shades but one shade in particular: the pink of a guava skin. Speaking Malaysian, of course, does not confer color-blindness, but to an Anglophone such vagueness can seem like an awkward and inaccurate approach to color. Why not just coin a word for "pink" and have done with it?

Yet English does exactly the same thing. We have no equivalent of pink for the blue portion of the spectrum. If you are not content with the vagueness of "light blue," you have no choice but to get hyper-specific—"robin's-egg blue," for instance. In other words, there's a chromatic gap in our language just as big as the one in Malaysian. But if you're like most native English speakers, you've probably never noticed it.

In contrast, Russian speakers learning English notice it right away: Their language divides up our "blue" into two colors, the paler *goluboy* and the darker *siniy*. What's fascinating is that these distinctions are more than technicalities. They become hardwired into our brains. Neuroscientists have found that native Russian speakers are measurably faster than native English speakers at distinguishing dark-blue shades from lighter ones, presumably because, in their minds, the difference between *goluboy* and *siniy* is clear-cut.



DIVIART / SHUTTERSTOCK

As language-bound human beings, we still require the semantic construct of agreed-upon labels.

As language-bound human beings, struggling to understand life's complexities, we still require the semantic construct of agreed-upon labels. A team of biologists, Francine Pleijel and George Rouse, have proposed the LITU, or "least-inclusive taxonomic unit," to replace the concept of species entirely. These would be provisional identities, which they describe as "statements about the current state of knowledge (or lack thereof)"—snapshots rather than static points, documented under the assumption that they might change as more genetic information becomes available.

This would move us away from lectotypes, allotypes, and other type specimens, a shift Pleijel and Rouse strongly advocate. According to them, "making taxonomists decide that a few dead specimens represent a species is an extravagant extrapolation that has no place in science." Scientists are "forced by the existing codes of nomenclature to describe organisms as species when in fact they generally have no idea of what is going on in nature."

***PHYSARUM POLYCEPHALUM* DEFIES** the foundations of Linnean thought. It is an ordinary tree slime, common in European and North American forests, classified and labeled in 1822 but otherwise ignored until 1970, when a teaching assistant at Iowa State University discovered a surprising characteristic: The slime not only had an immune system but one that functioned externally rather than internally.

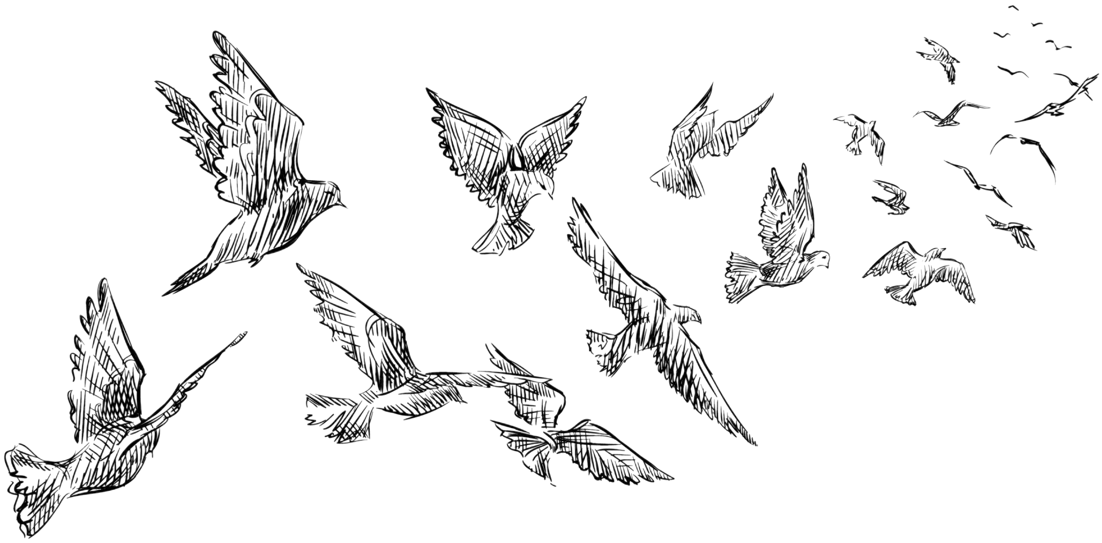
A sample of *polycephalum*, taken from a rotting elm log, kept infections at bay by secreting an antiviral substance so potent that when sprayed upon crops it was 100 percent effective in eliminating tobacco mosaic, a potentially devastating virus that blighted not only tobacco plants but tomatoes, peppers, and cucumbers as well.

Over the course of the past five decades, more of the organism's extraordinary aspects have come to light. As we've now discovered, it is neither an animal, a plant, nor a fungus. It can hibernate for years at a time. It has no musculature, yet it moves itself at a brisk 1.6 inches an hour. It is, somehow, a single-celled organism. (The *Guinness Book of World Records* proclaims it the largest cell on the planet.) If separated, segments are fully capable of operating independently, then reintegrating into the whole. They can even merge seamlessly into different specimens, gathered from different locations. Individual existence, it appears, is optional.

Its seeming simplicity belies an extraordinarily complicated sex life. Instead of two genders, male and female, *Physarum polycephalum* has 720 distinct forms of mating pairs, methods of inducing genetic variety that are the functional equivalent of genders. Sexuality and reproduction, as we've come to understand, accommodate a multitude of themes and variations.

Physarum polycephalum is also capable of learning. In order to most efficiently find food sources, it spreads itself out in a pattern both expanding and self-correcting, until it has covered the maximum amount of territory with the least amount of resources. By this measure, it can be seen as intelligent: The highly efficient networks it creates can find the quickest path out of a labyrinth or the shortest routes to connect multiple locations. In one experiment, it was presented with multiple food sources (in this case, oat flakes), placed in a pattern that replicated the geographic locations of Tokyo and 36 towns in the surrounding region. The slime mold reached out to all food sources with pathways that nearly replicated the Japanese rail system connecting those locations—a system carefully designed by humans to operate as efficiently as possible.

Despite its lack of a central nervous system, much less a brain, it's also capable of remembering. Somehow, it manages to retain what it's learned. If placed in the same labyrinth weeks apart, it will recognize the maze and re-create its previous escape route. Even a small piece of the original will do the same.



We don’t fully understand *polycephalum*’s intelligence, but that’s not keeping us from collaborating with it. In fact, we’ve recently recruited it to help us explore the cosmos. Current astrophysical theory holds that following the Big Bang, all matter in the universe dispersed in a pattern creating filaments between adjacent galaxies. Physical evidence of this dispersal is difficult to discover, since the filaments consist of thin, diffused streams of hydrogen gas. Astronomical instruments can detect these filaments, but only if pointed directly at them.

How to point the instruments in the right direction? By predicting in advance where these streams will be. To do that, astrophysicists have turned to *polycephalum*, harnessing the same efficiency it uses to solve mazes and re-create the Tokyo metropolitan train system. Using an artificial intelligence program designed to emulate the spore as closely as possible, they’ve been feeding it galactic maps and asking it to make connections. “A slime mold creates an optimized transport network, finding the most efficient pathways to connect food sources,” observes Joseph Burchett, the project’s chief researcher. “In the cosmic web, the growth of structure produces networks that are also, in a sense, optimal. The underlying processes are different, but they produce mathematical structures that are analogous.”

So far, the project has traced the connections between more than 37,000 galaxies. It’s just getting started, but it’s already demonstrated the power of shifting our perception of the living. Of approaching nature not as static objects to be inventoried, but as dynamic, interdependent manifestations of a greater whole.

To exist is to coexist. To be is to be in conversation.

In the words of pioneering 18th-century French naturalist Georges-Louis de Buffon: “Nature is not a thing, for this thing would be everything.”

Jason Roberts is an author of narrative nonfiction and fiction, living and working in Northern California. His previous book, *A Sense of the World: How a Blind Man Became History’s Greatest Traveler*, was a finalist for the National Book Critics Circle Award.

KAMIESHKOVA / SHUTTERSTOCK

God Does Play Dice with the Universe

A bold new theory reconciles gravity and quantum physics. If it's right, Einstein was wrong.

BY SABINE HOSSENFELDER

PLEASE EXCUSE ME for being excited, but this hasn't happened for more than four decades: Physicists have found a new approach to solving a problem which is almost a century old—how to combine quantum physics with gravity. The new idea comes from Johnathan Oppenheim, a professor of quantum theory at University College London, and he has dubbed it "Post-Quantum Gravity."

As I wrote previously in *Nautilus*, Oppenheim's theory could be what physicists have been missing. His idea is, on the face of it, quite simple: Rather than trying to give quantum properties to gravity, just make gravity as random as quantum physics, so that the two fit together. If Oppenheim's right, it would mean Einstein was both right and wrong: right in that gravity remained a classical, non-quantum theory, and wrong in that God did play dice indeed.

Now Oppenheim and his collaborators are saying that their idea doesn't just reconcile quantum physics and gravity, it also explains dark matter and dark energy. "Folks, something seems to be happening," Oppenheim wrote on X (formerly known as Twitter), sharing his research. "We show that our theory of gravity ... can explain the expansion of the universe and galactic rotation without dark matter or dark energy."

The problem that Oppenheim set out to solve is that quantum physics and gravity don't get along with each other very well. Quantum physics is what we call a non-deterministic theory. It has a random element, built-in uncertainty, and limits what you can do and know. We often say that quantum particles can be in two places at once, but really what the math shows is that it doesn't make sense to say they are in any particular place. They just don't have places.

The alternative explanation to dark matter is that the law of gravity needs to be changed.

Gravity on the other hand is described by Einstein's theory of general relativity. It assigns a time and place to everything. It is deterministic, the future follows from the past, and the only uncertainty it has is that which stems from our own lack of knowledge. It does not cooperate with the non-deterministic behavior of quantum particles.

There have been many attempts to unify the two and create what is known as a theory of quantum gravity. The best-known approaches give quantum properties to gravity and include string theory, loop quantum gravity, and asymptotically safe gravity. The path less taken is to leave gravity a non-quantum theory—a "classical" theory as physicists say—or to change something about quantum physics.

An example is Roger Penrose's idea that gravity is the reason why we never observe large objects being in two places. This and similar ideas have not worked out all that well, primarily because random jumps of particles in quantum physics describe our observations well, and yet gravity can't accommodate them.

Oppenheim's new approach overcomes this problem by leaving gravity a non-quantum theory, but giving it a random element. This randomness of post-quantum gravity doesn't come from anything else. It's a fundamental ingredient—the starting point. This is just like how the randomness of quantum mechanics does not come from anything else—it's fundamental, a starting point, just a property of nature.

The innovation that Oppenheim brought is that he found a way to combine the mathematics of both types of randomness into one framework. In this post-quantum theory, gravity remains non-quantum, and particles remain quantum. However, these two sectors communicate with each other because particles have gravity and that gravity in return influences the particles. In Oppenheim's theory, this works without contradictions because these two randomnesses fit together. But in return, this subtly changes both quantum physics and gravity.

In a recent paper, which has not been peer-reviewed, Oppenheim and his co-author Andrea Russo, a graduate student at University College London, say that this randomness changes the law of gravity such that it does away with the need for both dark matter and dark energy.

Dark matter and dark energy are terms that astrophysicists have given to two hypothetical constituents of the universe. Neither has ever been directly observed; astrophysicists have merely indirectly inferred their presence from their gravitational effects. They have added dark matter to explain, among other things, why galaxies rotate faster than expected and gravitational lenses are stronger than expected. They added dark energy to explain why the universe doesn't just expand, but the expansion also gets faster—no normal type of matter or energy could make that happen.

The alternative explanation to dark matter and, possibly, also dark energy is that the law of gravity needs to be changed. It wouldn't have to be changed at large distances—that doesn't work very well because galaxies come in many different sizes and we observe noticeable effects of dark matter at different distances from the center. Rather, it turns out that the best way of modifying the law of gravity is to change it when the acceleration acting on a star is very small—exactly what Opppenheim and Russo say they find in their post-quantum gravity.

PAGE 74: MARCEL DRECHSLER / SHUTTERSTOCK

Problem solved? Well, maybe, but I think it won't work.

This modification of Einstein's gravity at small accelerations is known as Modified Newtonian Dynamics, MOND for short. The reason this modification at small acceleration can appear as if there were dark matter is that the acceleration, on average, depends on the strength of gravity. If you are near a planet or a sun, then you experience a noticeable pull of gravity from those heavy objects. If you interpret that as a force, then that gives rise to an acceleration. The farther away you are from heavy objects, the smaller the acceleration.

However, the overall gravitational pull coming from an entire galaxy gets smaller the farther away a star is from the galactic center because most of the mass of the galaxy sits in the center. It turns out that if you assume that gravity gets stronger at small accelerations, then that can explain the observations attributed to dark matter in galaxies. This is, in a nutshell, the idea of MOND.

Oppenheim now says that when he and his colleagues looked at the changes to the law of gravity from the gravitational randomness, they saw a similar behavior: The smaller the acceleration of an object, the more it is affected by the randomness inherent in gravity. They derive an equation that is similar to Newton's law of gravity for the Newtonian gravitational potential, which is the quantity from which physicists derive the gravitational force. However, it is not the exact same equation, and its solutions have unusual contributions. They show that these extra contributions seem to be similar to what MOND offers: They make galaxies rotate faster. And for good measure, one of these contributions, they say, looks like dark energy. MOND itself does not account for dark energy, so this is quite a remarkable achievement.

Though I want to caution that in this most recent work they only look at galaxies, so they have not demonstrated that the quantity they identify as the simplest type of dark energy (a cosmological constant) indeed causes the universe to expand. For this, they refer to another "manuscript in preparation," so I guess we will hear more about this in the future. However, from my own experience, getting dark energy to come out right is not all that difficult. (I, too, have a theory which explains both dark matter and dark energy, it's just that no one cares about it.)

Problem solved? Well, maybe, but—call me a grumpy old woman if you must—I think it won't work.

The reason is that the equation they get is too simple. I suspect that it works for one galaxy at a time, but it will not work for a set of many at once. This is because astrophysicists have observed that if we combine data from many galaxies, then some observable properties—such as the rotational speed and brightness—are correlated with each other. MOND explains these correlations; dark matter does not. To me this is the great appeal of MOND over dark matter. But the equations which seem to follow from post-quantum gravity do not have the right properties to explain these relations. That is to say, I suspect that as they investigate their equations further, they will find that they don't work as desired.

Of course I could be wrong. And so for me this is a win-win situation. Either I am right, or I am wrong and we are witnessing the birth of a theory that delivers what many of us have dreamed of.

SABINE HOSSENFELDER is a theoretical physicist at the Munich Center for Mathematical Philosophy, in Germany, focusing on modifications of general relativity, phenomenological quantum gravity, and the foundations of quantum mechanics. She is the creative director of the YouTube channel "Science without the gobbledygook" where she talks about recent scientific developments and debunks hype. Her latest book is *Existential Physics: A Scientist's Guide to Life's Biggest Questions*. Follow her on X (formerly known as Twitter) @skdh.

Part-Time Climate Scientist

A humble steam engineer put humans in the driver's seat

BY SIDNEY PERKOWITZ

O**N A WEDNESDAY** in February 1938, Guy Stewart Callendar—a rangy, soft-spoken steam engineer, who had turned 40 just the week before—stood before a group of leading scientists, members of the United Kingdom's Royal Meteorological Society. He had a bold idea to share: Humans' burning of fuel was making the planet warmer.

By Callendar's calculations, over the past half century, humanity had added 150 *billion* tons of CO_2 to the atmosphere, raising the average global temperature about 0.03 degrees Celsius per decade—a trend, he noted, that could accelerate.

Callendar, an engineer whose day job was concerned with steam engines and turbines, knew he was going up against mainstream scientific wisdom. As he wrote at the very beginning of the paper detailing his findings, he was well aware that few scientists "would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale."[1] But calmly, methodically, he proceeded.

Sure enough, Callendar's presentation immediately met skepticism. Sir George Simpson, a prominent scientist soon to head the Royal Meteorological Society, dismissed the proposed link between rising CO_2 levels and temperature as "rather a coincidence." He also implied that a non-expert could not possibly understand atmospheric processes well enough to calculate the effects of solar radiation which Callendar had asserted was being absorbed in greater quantities by increased CO_2 in the atmosphere. Others pointed to alleged shortcomings such as the supposed unreliability of Callendar's data.

Callendar lucidly answered these criticisms. By prevailing scientific standards, he truly was no expert, though. He was not a Ph.D. scientist but held a certificate from an engineering college; he analyzed climate not within a large research institution but worked alone, at the home he shared with his wife and their two young daughters. But Callendar was not entirely an outsider to rigorous scientific research. He was the son of Hugh Callendar, a distinguished British physicist called a "universal genius" by Nobel laureate Ernest Rutherford.

Hugh Callendar had studied radiation, meteorology, and many other subjects. With an improved type of thermometer he developed, he also gathered unique, widely used data about steam and steam engines. His son Guy was raised in a "household filled with books and a vast array of technical gadgets," according to Guy's biographer James Rodger Fleming. Guy's scientific education accelerated when he apprenticed in his father's lab at Imperial College London in 1922, where Guy learned to perform painstaking research. However, he did not choose academia. After his father died in 1930, he used his knowledge of steam to become a steam engineer.

> Many people thought it impossible that humanity could upset a seemingly stable natural—or divinely ordained—planetary order.

With this background, the younger Callendar had been excellently, if unusually, trained in physics and as a careful researcher. This prepared him to deeply explore the possibility that human-produced CO_2 changed global temperatures, an idea hinted at but rejected in the 19th century.

In 1856, American scientist Eunice Foote had first shown that atmospheric CO_2 and water vapor strongly absorb heat from sunlight.[2] Later, Irish physicist John Tyndall proved that the absorption occurs at infrared wavelengths and thereby discovered the greenhouse effect. Heat from sunlight radiates from the Earth's surface as infrared light. Before this heat escapes into space, it is absorbed by CO_2 and water vapor, and the accumulated heat warms the Earth. Water vapor was thought to be more important than CO_2 in this process. But in 1896, future Nobel laureate Svante Arrhenius argued that CO_2 could have outsized effects. He calculated that the added CO_2 from burning coal could change global temperatures, although based on current industrial production, that would take centuries.

However, Arrhenius' calculation was unpersuasive. The science of the time did not fully understand how CO_2 absorbs infrared light, and many scientists thought that added CO_2 could never be a significant factor. Moreover, the calculation was purely theoretical; it was not supported by actual evidence of rising CO_2 levels or world temperatures. Also many people, scientist or not, thought it impossible that humanity could upset a seemingly stable natural—or divinely ordained—planetary order. For these reasons, Arrhenius' result was largely ignored.

Callendar, however, presented real evidence for a long-term connection between anthropogenic (that is, human-produced) atmospheric CO_2 and a warming trend occurring in the present, not the far future; then he explained the trend with a scientifically sound theory. And despite his initial poor reception, he pressed on with more research to support his conclusions.

Callendar's bold persistence in the face of a dubious scientific community was surely bolstered by confidence in his own scientific training and judgment, which he had received under his father's tutelage.

One need was for good data. Callendar found the trends he reported by gathering far-flung reports of early measurements of atmospheric CO_2 and by poring over decades of data in *World Weather Records* from the Smithsonian Institution, with its "mass of statistical detail, including many millions of accurate and standardized readings of temperature," as he described in his 1938 paper. He scrupulously selected the most reliable CO_2 data and chose 147 sites that gave a balanced picture of global temperatures. He laboriously mined and analyzed these datasets by hand, a precursor to what scientists now do routinely—in a digital flash—with massive collections of big data.

The second need was to explain the observed trends. Callendar used fundamental physics to model how

CO_2 in the atmosphere changes the temperature of the Earth's surface. This model, also calculated by hand, was a precursor to modern computer-based (likely eventually AI-based) simulations that are essential for climate research and prediction.

The claims in Callendar's daring paper have been borne out in the subsequent eight decades of science. He was the first to find real evidence that the human burning of fossil fuels had already increased atmospheric CO_2 (by 6 percent over that past half century)—and to determine the parallel increase in temperature over the same period. His calculations were the first analysis that demonstrated *how much* the rise in CO_2 had actually changed temperatures. Callendar also determined that most of the human-added CO_2 would not be removed by the natural cycle that transports carbon through the Earth's systems, so he thought anthropogenic atmospheric CO_2 would continue rising.

There was more. He predicted how far climate zones would shift, calculating a retreat of about 22 miles and 79 miles for polar zones in the 20th and 22nd centuries, respectively. He pinpointed a trend in the data for higher-elevation sites to warm more quickly than those closer to sea level. He accounted for increased "heat-island" effects of urban areas as they grew and developed over his study period. (So, he determined that the highest-quality readings came from isolated places like Upernivik, Greenland and Apia, Samoa.) And to further challenge his own ideas, he looked back in geological time to investigate the last ice ages and warming periods, to see if similar natural forces could be at play in his era—but could not make a plausible case for it.

Thus, Callendar concluded, "the combustion of fossil fuel, whether it be peat from the surface or oil from 10,000 feet below," is the cause of the increase in global temperatures. Although he had solid arguments to support this, a single research paper could hardly convince a scientific community that doubted its whole premise. Nevertheless, merely putting forth what came to be called the Callendar Effect, with the questions and criticisms it evoked, propelled research by others, and by Callendar himself. In nearly three dozen later papers, he refined some of the numbers he cited in 1938 but never changed his overall claims.

COURTESY OF UNIVERSITY OF EAST ANGLIA ARCHIVE / WIKIMEDIA COMMONS

INCONVENIENT TRUTH-TELLER Guy Stewart Callendar, a scientifically trained steam engineer, spent years gathering and crunching data by hand to arrive at a new way of looking at the world—and humans' power to change it. His persistence in arguing for CO_2's role in raising global temperatures paid off only after his lifetime.

By the time Callendar died in 1964, scientists had not yet widely accepted the reality of human-induced warming, although he lived to see the first signs of a shift. In 1960, Charles Keeling of the Scripps Institute of Oceanography began publishing data from the pristine air in Antarctica and later at Hawaii's Mauna Loa volcano that clearly revealed a growing level of CO_2 (he showed it at 315 parts per million in 1958; today it is 421 ppm; in the pre-industrial 19th century, it had rested around 280 ppm).[3] Other evidence mounted, and a tipping point came circa 1990, when the United Nations Intergovernmental Panel on Climate Change, scientific societies, and researchers began reaching a consensus that human-caused warming is underway and would cause dire effects, as is now happening.

SO VAST A SCALE By the early 20th century, fossil fuel-fired industry peppered many once-natural landscapes. At the time, these were often seen as landmarks of human progress. Not many "would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale," Callendar wrote in his landmark 1938 paper.

EVERETT COLLECTION / SHUTTERSTOCK

Callendar would have been surprised to learn of these negative outcomes from the warming he had found. He had been quite confident this warming "is likely to prove beneficial to mankind." Europe's Little Ice Age (circa 1300-1850)—during which the average temperatures dropped some 2 degrees Celsius in the U.K., leading to crop failures, starvation, and mass death—had concluded only during his grandparents' lifetimes. A little extra warmth, Callander posited, would not only expand the range and seasons of crops, but also, he concludes, "the return of the deadly glaciers should be delayed indefinitely." He estimated that the planet held enough fossil fuels to multiply the amount of CO_2 in the air tenfold. Only later did computer climate modeling begin to foretell the unwelcome effects from global warming.

Modern reviews show that Callendar's work was more accurate and prescient than its critics. In 2013, the

Callendar knew he was going up against mainstream scientific wisdom.

75th anniversary of the 1938 paper, and again in 2021, the temperatures Callendar cited for 1880 to 1935 were shown to agree well with new, more comprehensive data. Another paper in 2016 examined the pioneering temperature calculations by Arrhenius and Callendar.[4] Callendar was judged to have used better data and a more realistic atmospheric model, but like Arrhenius, he underestimated the growth rate for atmospheric greenhouse gasses. Correcting for this, the authors found that Callendar's approach, projected 62 years forward to 2000, predicts a global temperature rise of 0.52 degrees Celsius, very close to the measured value of 0.6 degrees Celsius. These reviews call Callendar's work "meticulous" and "remarkable," and note that the physics he used is still the core of modern climate models.

Callendar's 1938 paper has now been so heavily referenced that it has become a classic, but it was hardly cited at all during Callendar's lifetime. According to Callendar's biography, he felt some frustration over his lack of recognition. In 1960, listing reasons for the unpopularity of the Callendar Effect among leading climate scientists, he put the last reason as, "They did not think of it themselves!" Such feelings, however, had not kept Callendar from steadfastly continuing to make his case.

When Guy Callendar stood before the Royal Meteorological Society in 1938, he began a revolution in thinking about humanity's effects on its own planet—one that is ongoing. Other scientists eventually joined, but it was Callendar who kept the revolution alive for decades. Described as a balanced and unassuming person, devoted to work and family, he likely never would have called himself a rabble rouser. Today, at last, we clearly hear and appreciate that quiet voice.

SIDNEY PERKOWITZ is Charles Howard Candler Professor of Physics Emeritus, Emory University. His latest books are *A Short Introduction to Physics*, *Real Scientists Don't Wear Ties*, and *Science Sketches: the Universe from Different Angles*.

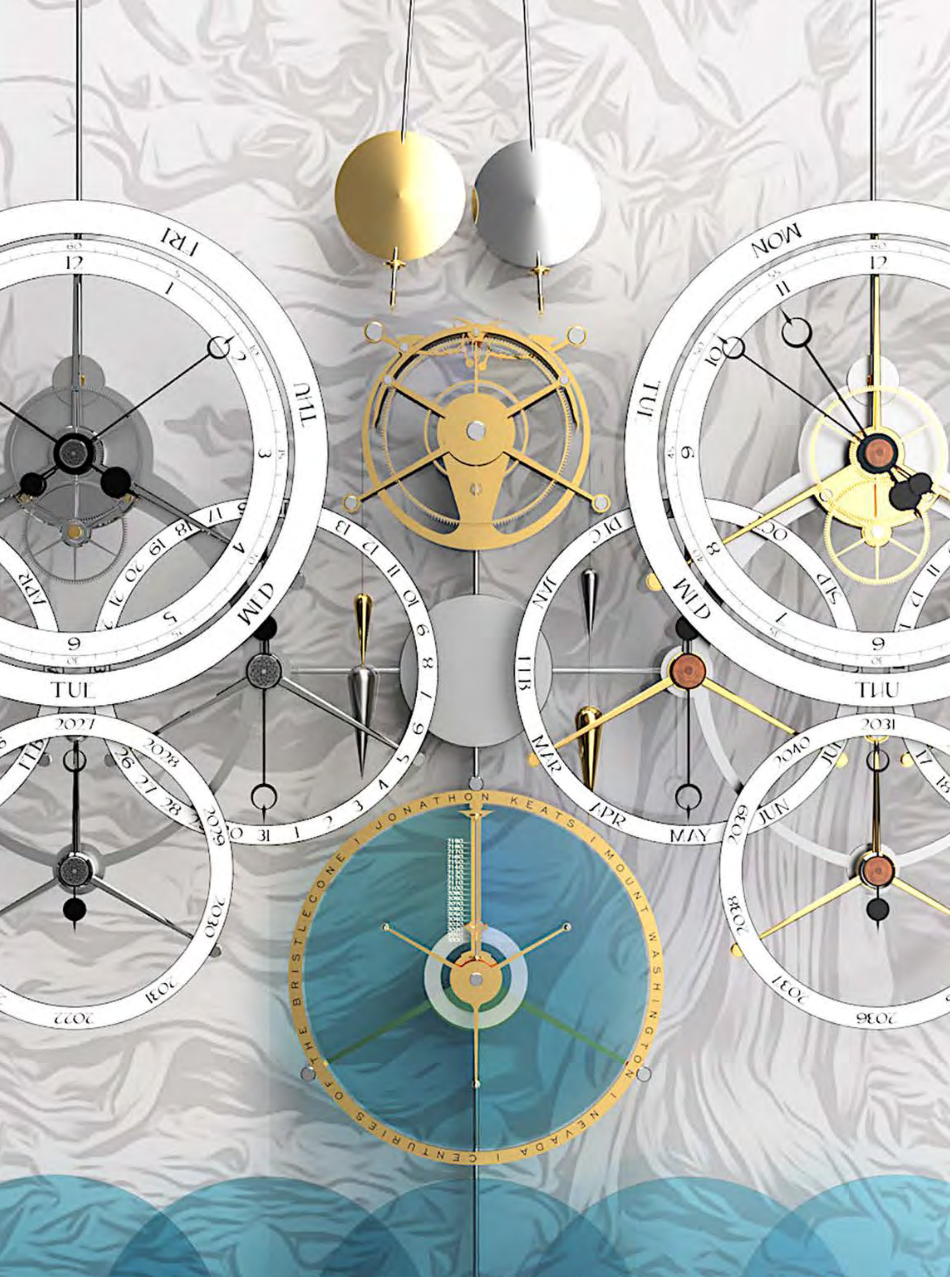
REFERENCES

1. Callendar, G.S. The artificial production of carbon dioxide and its influence on temperature. *Quarterly Journal of Royal Meteorological Society* **64**, 223-240 (1938).

2. Foote, E. Circumstances affecting the heat of sun's rays. *American Journal of Art and Science* **22**, 382-383 (1856).

3. Keeling, C.D. The concentration and isotopic abundances of carbon dioxide in the atmosphere. *Tellus* **12**, 121-241 (1960).

4. Anderson, T.R., Hawkins, E., & Jones, P.D. CO_2, the greenhouse effect and global warming: From the pioneering work of Arrhenius and Callendar to today's Earth system models. *Endeavour* **40**, 178-187 (2016).


CENTURIES OF THE BRISTLECONE | JONATHON KEATS | MOUNT WASHINGTON | NEVADA |

A Revolution in Time

Why clocks need to follow the tempo of nature

BY JONATHON KEATS

IN THE FALL OF 2020, I installed a municipal clock in Anchorage, Alaska. Although my clock was digital, it soon deviated from other timekeeping devices. Within a matter of days, the clock was hours ahead of the smartphones in people's pockets. People figured something was awry.

PHILIP ABERNETHY; COURTESY OF THE NEVADA MUSEUM OF ART

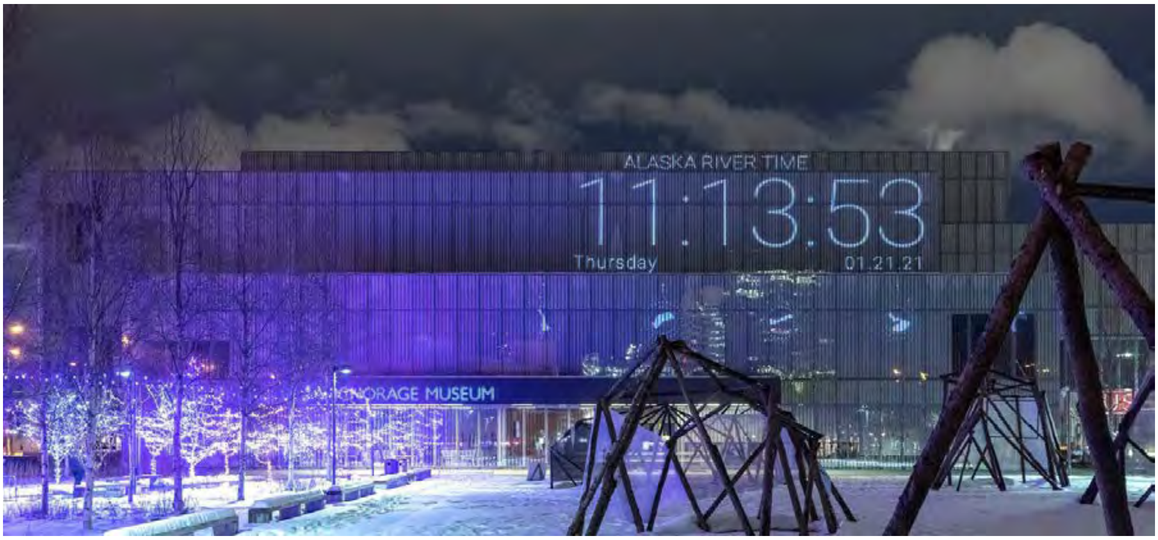
But the clock wasn't defective. It was just unconventionally regulated: I calibrated the flow of time to coincide with the flow of glacial rivers. Impacted by climate change, the rivers were flowing faster than in the past. Or from the perspective of the rivers, everything else was happening more slowly.

As I wrote in a previous *Nautilus* article, "Philosophy Is a Public Service," my training is in philosophy, which I practice in public. My ambition is to engage as broad a population as possible in the realm of ideas, encouraging people to explore the world in which we live, and to chart possible futures for our cities, our environment, and our planet. I believe that collective reflection and anticipation are necessary for our survival—especially in this period of ecological upheaval—and that philosophy needs to be a public service as much as cartography and timekeeping.

I created *Alaska River Time* while I was a visiting artist at the Anchorage Museum. I developed this art installation out of the conviction that all the clocks I'd ever encountered were malfunctioning. I'm not claiming they're imprecise. The oscillations of atomic clocks at the National Institute of Standards and Technology are so consistent that they will neither gain nor lose a second over billions of years. Even Big Ben, constructed in the 1850s, has such a steady beat that minor adjustments are required only once a week.

What is troubling to me is their *accuracy*, or in other words the degree to which the steadiness of clocks corresponds to time as actually experienced by people and other living beings. Time seldom keeps a steady beat in nature. Circadian rhythms fluctuate, as do rates of growth and decay.

Given that life on a river is synchronized by the fluctuating discharge of water, flow rate has greater salience than the split-second pulsations of a strontium atom, or even the planetary rotation that organizes our days in 24-hour cycles. When we look at a river



OF TIME AND THE RIVER The Anchorage Museum is an urban landmark and a local gathering spot. That makes it the perfect setting for a concert or picnic—or a municipal clock. Back in 2020, I worked with a software developer to introduce Alaska River Time to Anchorage residents with a projection on the museum façade. We chose five rivers, each impacted by climate change in myriad ways. The U.S. Geological Survey website provided us with realtime flow data, which the software compared to the average flow to determine the clock rate. Each river was given its own clock face, and they were averaged in a digital display of Alaska River Time.

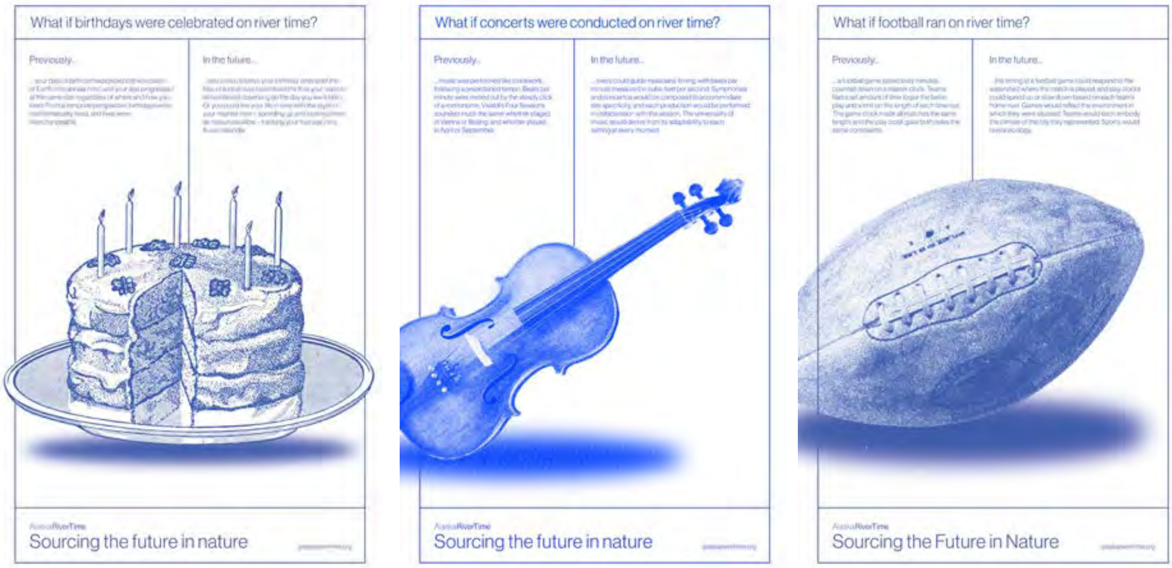
COURTESY OF THE ANCHORAGE MUSEUM

from the perspective of the clock on our smartphones, we perceive natural deviations as imperfections. We expect the Amazon to behave like Amazon.com. We expect nature to run on time to meet the demands of an economy that considers unpredictable conditions to be a logistical problem.

Our temporal intolerance is intolerable from the standpoint of planetary well-being. Climate change shows that nature cannot be pushed around indefinitely. Logistics must be accountable to more than market demands. Similarly, for a clock to be accurate, I believe that it must be sensitive to environmental variations. From the perspective of NIST, it must be *imprecise*.

HOROLOGY, THE PRACTICE of time measurement, is a conservative trade, motivated by the age-old desire to bring order to the world. Clocks promise that life will have the certainty of astronomy or physics by gearing living systems to operate like machines.

Ironically, even bringing that certainty to a tabletop mechanism proved terribly difficult, confounding inventors for thousands of years. Driven by spilling water, clocks slowed down as they lost ballast. Driven by falling weights, clocks sped up as the mass accelerated. Discovered by Galileo, who observed the periodic motion of a swinging chandelier in church one day, the pendulum provided the first scientific solution.



HAPPY RIVER DAY I want people to integrate river time into their daily lives. I don't want it merely to be an abstract concept (as happens all too often when the public encounters climate science). To encourage Alaskans to apply river time meaningfully, I worked with the Anchorage Museum on a series of 10 posters with 10 different propositions. For instance, I suggested that river time be adopted as a legal time standard, and that it be the basis for the school year and the payment of interest on municipal bonds—even football games. By proposing that people celebrate their birthdays on river time, I sought to make the experience of river time personal, to encourage periodic visits to the local waterway as an alternative to blowing out candles on a birthday cake.

COURTESY OF THE ANCHORAGE MUSEUM

In theory, the rate at which a pendulum swings is determined by its length from pivot to bob. In ideal conditions, the pendulum would oscillate at that rate indefinitely. From the moment that Christiaan Huygens operationalized Galileo's observation in the first functional pendulum escapement until electronics supplanted mechanics, engineers worked to approach that ideal by making the periodic motion of timekeeping mechanisms more robust and reliable.

The greatest attention was devoted to isolating the pendulum from all external conditions. New alloys were formulated to expand and contract as little as possible with changes in temperature, so that the pendulum length always remained the same. The clock case was designed to isolate the pendulum from changes in humidity and air currents. With extraordinary ingenuity, clockmakers extracted the clock from the world, dematerializing the hours. Antique timepieces are some of the most luxurious objects ever created, yet paradoxically all the guilloché and gilding was directed toward transforming time into an abstraction.

There is an older tradition that stands in stark contrast to horology. The origins are prehistoric, and the practices were still prevalent at the dawn of the Common Era. I find one of the most vivid descriptions in Pliny's *Natural History*, the foremost encyclopedia of the Roman Empire. "I have given you plants that mark the hours, and in order that you may not even have to avert your eyes from the Earth to look at the sun," Pliny wrote, assuming the voice of nature:

ARBOREAL TIME In the fall of 2023, I visited the bristlecone pine trees atop Mt. Washington with Long Now Foundation colleagues. We climbed to an elevation of 11,600 feet, the trees' natural habitat. (They thrive in harsh conditions, which is why I was dressed in a parka.) Up on the mountain, on Long Now property, we selected four trees of different sizes, which we designated as calibration points for arboreal time. In order to find the calibration points in the future, I attached a ceramic tile to the rockface nearest each tree. The tiles are numbered and attached to the stone with mortar I had to prepare on the spot. At that elevation, mortar dries slowly, but it can last for centuries.

JAMES HOME; COURTESY OF THE LONG NOW FOUNDATION

> "Why then do you still look higher and scan the heavens themselves? Lo! you have Pleiads at your very feet." Glow-worms do not make their appearance on fixed days or last a definite period, but certain it is that they are the offspring of this particular constellation. Consequently anybody who does his summer sowing before they appear "will have himself to thank for labour wasted."

In Pliny's account, time is relational. Natural phenomena are correlated in predictable ways, either because they are causally linked or because they're triggered by similar environmental conditions. Timekeeping is a way of anticipating phenomena that are important based on those that are prevalent.

In modern scientific terms, glow-worms are *phenological indicators*, meaning that they signal seasonal changes in the environment as a whole. I should emphasize that they're hardly unique in that respect. From North America to Asia, indigenous peoples still rely on ecological calendars that name the months based on the natural events underlying traditional lifeways.

For the Haida people of British Columbia, the time of year corresponding to January/February is known as *hlgidguun kongaas*, or "Canada goose moon," referencing the geese flying down the coast. February/March is *taan kongaas*, or "black bear moon," marking the time when bears emerge from hibernation. The calendar indicates that bears will emerge after the geese arrive, while allowing this progression of events to drift forward or backward relative to the lunar cycle based on natural variability in climate conditions from one year to the next.

Another important feature of ecological calendars can be witnessed in *wiid gyaas*, the Haida month that typically aligns with April. Coinciding with the end of winter, *wiid gyaas* references the Swainson's thrush, which is known as the salmonberry bird in the Haida language. The song of this bird is not only the sound of springtime, but also calls upon people to forage for salmonberries, which might go unnoticed were it not for this creature's persistent beckoning.

The tight coupling of the Haida calendar with the ecology of British Columbia is a testament to the more than 14,000 years they've lived there, during which time they've synchronized their lifeways with the lives of

> For a clock to be accurate, I believe that it must be sensitive to environmental variations.

every other being. But the past reliability has become a source of vulnerability as anthropogenic climate change plunges April into February. What I'm saying is that the ecological calendar has inadvertently become an environmental indicator of global warming.

Ecologists and climate scientists are now collaborating with indigenous communities to revitalize ancient calendars by identifying current phenological correlations. For example, in the Pamir Mountains of Central Asia, farmers and herders have traditionally kept time by associating phenological indicators with parts of their body, counting from their toes to their head as winter leads into spring. Their bodies still provide convenient mnemonics, but they must now convene each year to reassess what counts and what it means. With this feedback, the calendar is self-correcting, but age-old rhythms have been supplanted by anxious contingency.

The time indicated by my fluvial clock is equivalently contingent, but the clock is intended to operate in a different context and with a different purpose. Instead of resetting the time periodically and using the discrepancy to recalibrate events such as the beginning of fishing season, I let the clock run free.

As I write these words, Alaska River Time is 3:14 AM on Nov. 30, 2024, nearly 10 months ahead of the Gregorian calendar. The fluvial calendar is ahead because Alaskan glaciers are melting more rapidly than in the past, and the speed of melting accelerates with every passing year.

The clock rate is a ratio between present conditions and the average flow over the last half century. When Alaska River Time is accessed online, you experience temporality from the rivers' perspective. When you live on river time, your clock is no longer insulated from the environment. Your schedule is set in relation to fluvial conditions.

RIVERS ARE NOT THE ONLY meaningful indicators of environmental conditions. Just as the time told by every river is inherently accurate even though the clock rate of two rivers may differ, all other life forms and living systems manifest time, and I believe that each has claim to equal authority.

STRING CALENDAR The age of a tree can be determined by drilling a core and counting the rings. The same technique can be used to determine the relative growth rate from year to year. This will be the basis for calibrating the clock we're installing at the Nevada Museum of Art. Although it isn't as precise, the growth rate can also be monitored by wrapping a string around the trunk. I created a string calendar for each of the bristlecones we'll use as calibration points for the clock—indicating future dates on wooden tabs that are spaced according to the trees' current growth rate—in order to encourage hands-on encounters with the trees. Handling the string proved unexpectedly difficult in the cold. I was pleased that it took time.

JAMES HOME; COURTESY OF THE LONG NOW FOUNDATION

At present I'm developing a clock that will be regulated by the growth of trees. The monumental electromechanical clock will be built at the Nevada Museum of Art in Reno.

There will be two faces and two pendulums. One will take orders from NIST in Boulder, Colorado. The other will be controlled by the growth of bristlecone pines on Mt. Washington in Nevada's Great Basin.

A collaboration with the Long Now Foundation, which owns the property where the trees grow, the timepiece will not only juxtapose time standards but will also mesh phenology and horology. All trees grow erratically, at least from a precisionist point of view. This can be seen in their growth rings, which vary in thickness from year to year, impacted by factors ranging from rainfall to the quantity of carbon dioxide in the air. Dendrochronologists use this variation to detect climate conditions in the past, treating trees as passive records. My clock puts the trees in an active position, directing their own observations of the environment forward in time. How thick is this year's ring compared to those in the past? The ratio sets the clock rate.

The traditional design of my clock is intended to be timeless. Given that bristlecones can live for as long as 5,000 years, and new fashions tend to peak in hours, the timelessness might be seen as an attempt to future-proof the device. However, my motivation is more philosophical than aesthetic, or rather the aesthetic properties are essential to its operation as a philosophical instrument.

INNER CLOCK OF TREES Mt. Washington is extremely remote. Few people will have the opportunity to visit. So I'm working with a master clockmaker to build a municipal clock that people will encounter at the Nevada Museum of Art in Reno. The design shown in this computer rendering is meant to familiarize people with arboreal time and to make it legible to anyone. The second face, indicating standard time, is intended to pose a challenge: Which clock do you trust? I hope that people take both measures seriously, and that the clock opens them to observing time in all phenomena, celestial and terrestrial. In simulations we've run, the two pendulums are mesmerizing to watch as they periodically fall into and out of sync. They make the internal life of the trees palpable. If you focus, you might even experience bristlecone time in your heart.

PHILIP ABERNETHY; COURTESY OF THE NEVADA MUSEUM OF ART

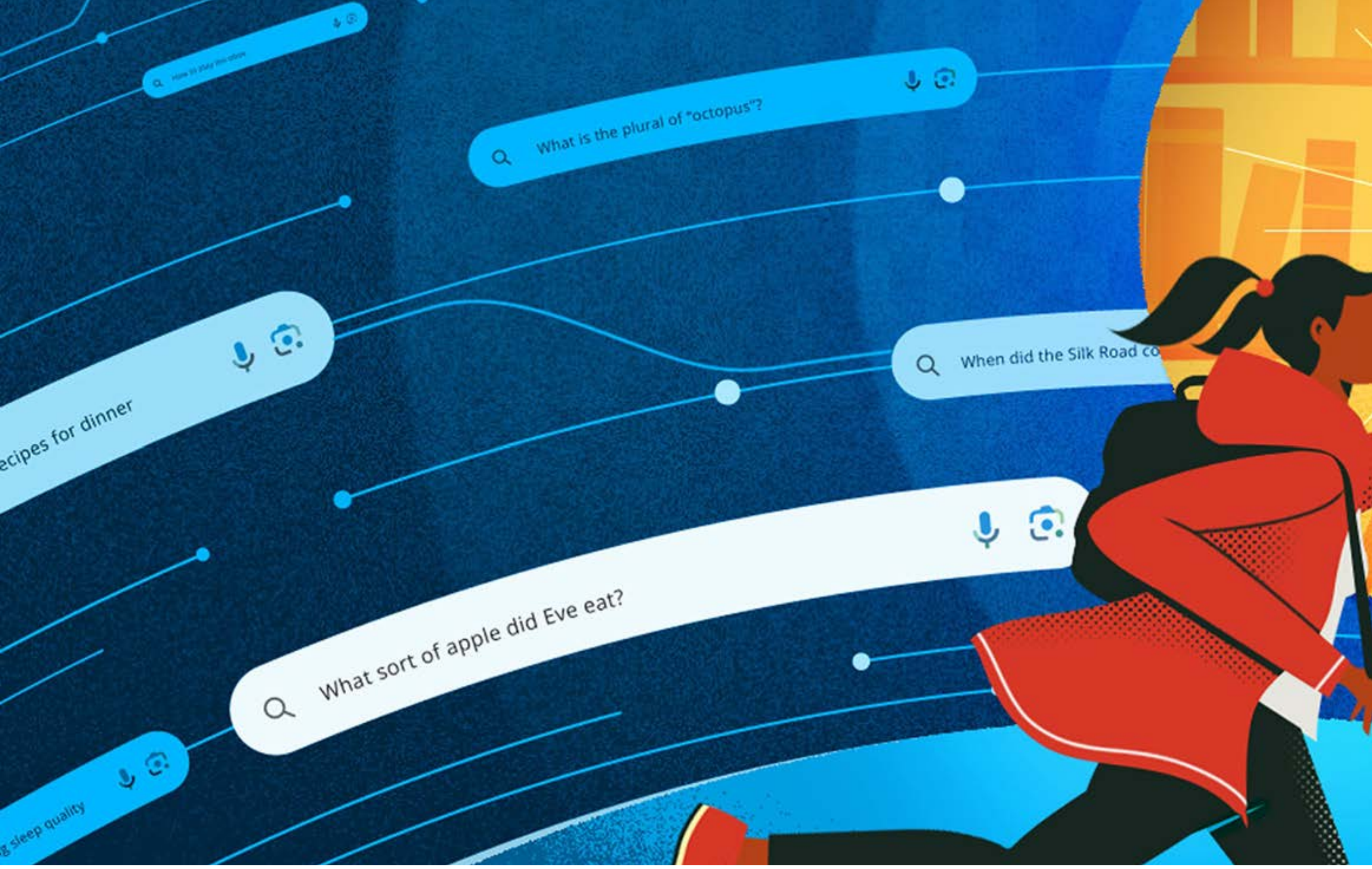
By taking up the vernacular of a pendulum clock, and even integrating decorative arts such as guillauché, this new municipal timepiece meets Christiaan Huygens and Big Ben on their own terms. It questions the clockwork logic that has driven society since precision became a precondition for accuracy.

In *Technics and Civilization*, the historian Lewis Mumford observed that the "essential nature" of the clock "dissociated time from human events and helped create the belief in an independent world of mathematically measurable sequences." On this basis, he set the clock above the steam engine as "the key machine of the modern industrial age."

Mumford wrote these words in 1934, decades before climate change was detected and steam power was identified as a culprit. The key question of our own time is whether we can counter the environmental devastation wrought by the industrial age and fossil fuels.

I think that Mumford was right. But I also believe that clocks might just be the machinery needed to set a post-industrial age in motion, if only they can be made compatible with life on Earth. Like *Alaska River Time*, clocks can redeem horology by subverting it.

JONATHON KEATS is an experimental philosopher, artist, and writer. He is currently a fellow at the Berggruen Institute, a research fellow at the Long Now Foundation, a research associate at the University of Arizona, principal philosopher at Earth Law Center, and an artist-in-residence at Hyundai, the SETI Institute, and Flux Projects. His most recent book is *You Belong to the Universe: Buckminster Fuller and the Future*. He is currently writing a field guide to more-than-human governance.



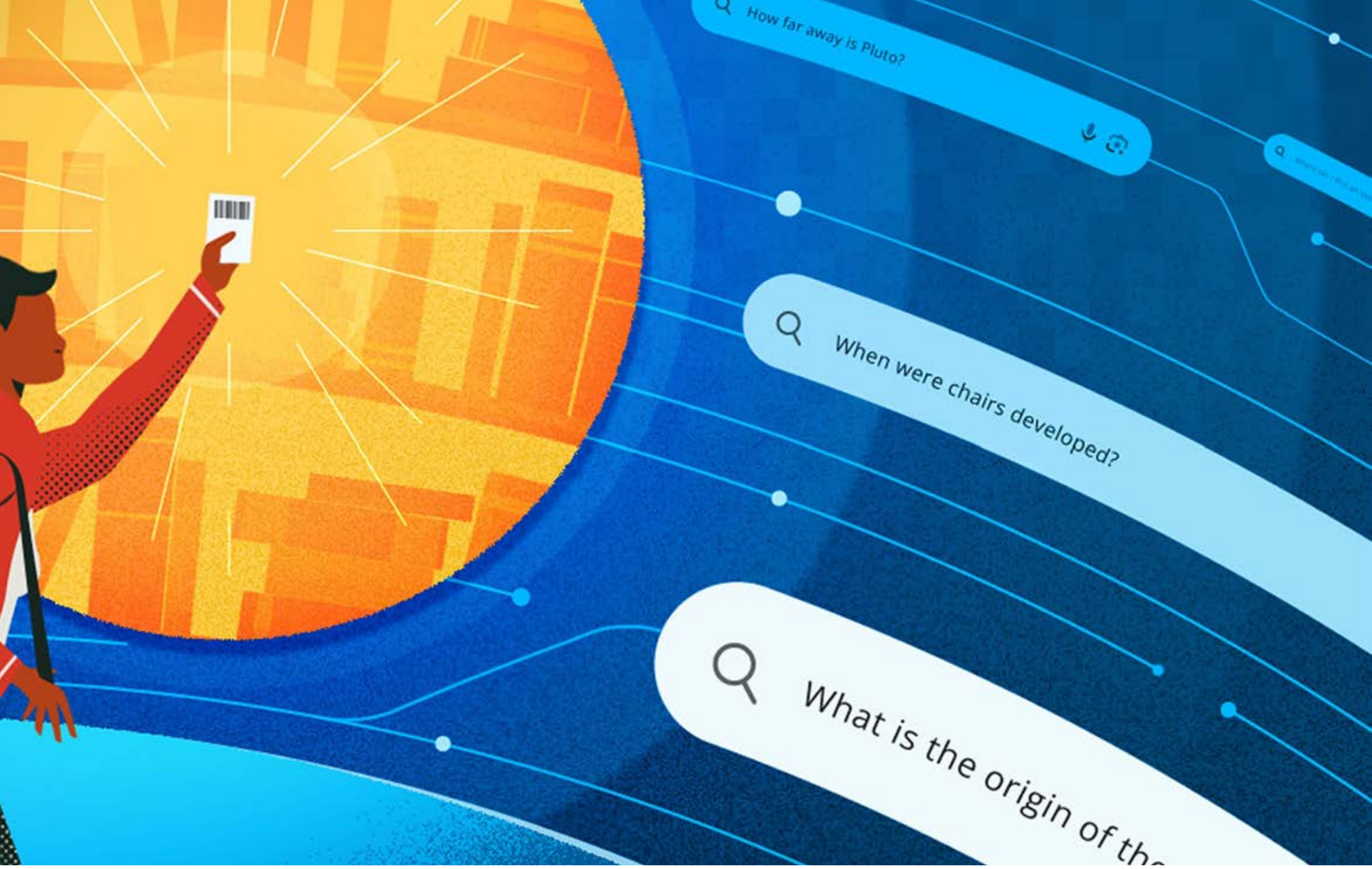
Viva la Library!

Rebel against The Algorithm. Get a library card.

BY CHARLES DIGGES

ILLUSTRATION BY MARK BELAN

W**E'VE ALL BEEN THERE.** In fact, I find myself there several times a day. A question emerges and my memory stumbles. Decades of education dematerialize into an expensive mist. I know I know this, or at least I should.



I reach for my phone and type:

Who painted that corner diner at night with those lonely looking people sitting inside?

But what if it hadn't been so simple? What if—instead of having my screen cluttered instantly with infinite reproductions of Edward Hopper's *Nighthawks*—I was forced to live in a period of contemplation? Of not knowing? Might that have generated a spark of curiosity?

If so, I might have found my way to the library. And while there, I might have stumbled on a good deal more about *Nighthawks* and its enigmatic portrayal of urban loneliness—as, once upon a time, as a Midwestern kid longing for a life in the big city, I did within the stacks at the Iowa City Public Library. There, I followed the streets of Hopper's metropolis to the stories of John Cheever and Ralph Ellison, their characters often under the spell of Duke Ellington and Dizzy Gillespie, whose records I checked out. I could step backward, too, following Hopper's urban themes to Degas and Manet—their gamines encountered with the longing felt in the pages of Proust.

Or I could fast forward through time, following the throughline of Hopper's influence on another painter, George Tooker, who focused a paranoid gaze on waiting rooms and subway platforms to paint a bureaucratized modern dystopia. From there, it was a short trip to Zamyatin's *We* or Orwell's *1984*. In the library, with its faint arboreal scent of binding glue, I was able to have my first encounters with a life beyond the prairies.

When I Google *Nighthawks* now, the Image Search feature of Google brings me first to advertisements for Amazon-peddled reproductions of the painting—some of them washed out and pale, others featuring the cast of *Star Wars* in place of Hopper's anonymous figures—all of them available for about $11.95.

The internet, writ large, is now a universal medium. In the beginning, we were told the digital sphere would bring us together to share information and expand our perspectives, and now, there's hardly a corner

NIGHTHAWKS Author Charles Digges learned about the rich culture that surrounds Edward Hopper's timeless painting at the library. To Google the painting, he found, is to desecrate it.

WIKIMEDIA COMMONS

of our lives that it hasn't touched. It governs nearly every aspect of how we read, learn, and connect to the larger world.

But while few parts of the world remain outside its reach, the internet leaves little room for discovery. Our curiosities in the digital environment are not so much sparked as they are confirmed. The system is designed to say "yes" to us, not challenge us. Over time, even the questions we ask begin to take on the smooth, antiseptic quality it was designed to reward. Digitalization has driven us further into ourselves and sects of the like-minded.

As they have done time and again, libraries have adapted to these technological changes. But they have also managed to maintain their value as places where learning is interpersonal and social. Libraries might be our last bulwark against the digital degradation of life and learning.

WHEN GOOGLE SEARCH WENT LIVE in 1998, so awesome was its reach that many thought it could herald the end of libraries as we knew them. There would be no more slogging through infinite stacks or grazing back periodicals to convert Fahrenheit to Celsius or to establish whether the philosophies of Levinas and Kierkegaard are compatible. Finding out how long it takes an eyelash to regrow, or how to build a doghouse, would become just a matter of asking the search bar. On offer was nothing short of the universal library, a revival of the Library of Alexandria that was envisioned as a model of the universe itself, an infinitely growing compendium of answers to every question, accessible to all.

But at Google's heart was a Faustian bargain. Access to a bottomless well of knowledge would come at the cost of us becoming a thinly anonymized data point, the contents of our searches surveilled and transformed into rocket fuel for Google's online advertising empire.

Libraries might be our last bulwark against the digital degradation of life and learning.

The longer we linger online and follow links, the more monetizable breadcrumbs we leave, and the more eerily personal the advertisements become.

Each day, Google processes 8.5 billon queries, slightly more than one for every person on Earth. How it makes sense of such volume is, of course, a closely guarded secret—a black box that is nearly impossible to crack. But in its early iterations, the fundamentals of Google's algorithm were not so dissimilar from the practices of librarians.

In the late 1990s, during the Web's infancy, Google had plenty of competition from the likes of Lycos, Yahoo, and AltaVista, whose searches were guided by typing in keywords. The results were middling. Google broke through the stagnation with its PageRank algorithm, which counted and indexed the number of high-quality links leading to any page.

Rather than using keyword matches, PageRank supposed that the best results would be websites that are linked to by many other high-quality websites (their quality, likewise, determined by the number of pages linked to *them*, and so on). This is borrowed from bibliometrics, the science librarians use to evaluate the penetration of academic papers based on how often they are referred to by other scholars. A librarian's eye is enough to establish that the papers an academic cites aren't gibberish. PageRank couldn't make that distinction. But newer search functions that Google has reportedly incorporated over the past few years, can.

Among these is MUM (short for Multitask Unified Model), a machine-learning Search tweak introduced in 2021. With MUM's help, Search can discern how words and concepts relate to one another and detect nuanced meaning and associations in queries, as well as take past search behavior into account. That's, essentially, how searching for "lonely people in a diner" led me to Edward Hopper.

For all that transformative technology, lately something about Search feels *off*. Billions of queries seem to be returning more and more homogenous results cluttered with links to e-commerce sites and prioritizing texts that read like they have been written by robots. As more and more people click on similar things, they reinforce the circularity.

In 2021, the same year MUM premiered, the question, "Has Google Search Become Qualitatively Worse?" was posed on a thread at *Hacker News*. "The results keep getting 'refined' so as to suit the popular

Tennis enthusiasts get clickable tennis content, cat lovers get feline content, wingnuts get wingnut content.

80 percent of queries, while getting much worse for any technical or obscure queries," responded a commentor with the handle "vgeek."

Xe Iaso, a programmer and tech blogger from Ottawa, Canada who has long observed Google's evolving algorithm, blames much of the change on the industry of search engine optimization, a global network of consultancy agencies that help their clients improve their visibility on Google.

At one time, many people created websites to share their expert knowledge about, say, radishes, and to "express themselves in new and interesting ways," Iaso writes. But the advent of online advertising—being able to place small ads on your site—changed web creators' incentives. "Now, instead of just making money selling radishes and radish consumption accessories, you could make money by people *viewing your website about radishes*."

Soon enough, the professional prognosticators stepped in. For the right price, they could help you design web pages that appear higher in the results that Google returns on a search. The consultants sell you all manner of tricks to draw people to your site so you can cash in on clickable ads. (You get a percent of the sales.) Strategies include incorporating links from other sites and soliciting sites to host your links. As the editor of a website myself, I am constantly barraged by search optimizers asking me to embed links to their material in what I publish. (I never do.) Because of slick optimization, more obscure, non-optimized content gets driven down farther in search results or gets skipped altogether. The optimization industry, Iaso told me, has turned the Web into an "inhuman Skinner box," where people thoughtlessly click from one titillating link to another.

In a 2024 paper, a group of German researchers concluded that "a torrent of low-quality content … keeps drowning any kind of useful information in search results" on all search engines, not only on Google. Over the course of a year, the researchers entered some 7,400 product review searches, and found that results containing "affiliated links"—or paid-for advertisements—surfaced more often than the far more numerous organic reviews that don't contain ads. Prioritizing paid advertisements over non-affiliated content, the authors write, creates "a conflict of interest between affiliates, search providers, and users," and corrodes the trust of users looking for high-quality, objective information.

In short, the more content on the Web is tricked out to draw our clicks, the more sequestered and siloed knowledge gets. The tennis enthusiasts get clickable

THE DREAM When Google Search first launched, on offer was nothing short of the universal library, a revival of the Library of Alexandria.

THEDARDANIAN / DEVIANTART

tennis content, cat lovers get feline content, the wingnuts get wingnut content. There's scant variability running contrary to the premise of any given search. Getting beyond the cycle requires the users themselves to stumble into something new—to exercise an intellectual agency that the algorithm so often seems designed to dull.

Regardless of how the clickable content reaches me, I find that instantaneous access to a gluttonous buffet of information has done something to the way I think—and it might not be good.

In a meta analysis called "The Online Brain," Joseph Firth, a mental health researcher at Australia's National Institute of Complementary Medicine, and John Torous, who directs the digital psychiatry division at the Beth Israel Deaconess Medical Center, and other authors, informs us that even "a short-term engagement with an extensively hyperlinked online environment (i.e., online shopping for 15 minutes)" does a number on our attention spans, compared to reading a magazine, which doesn't produce the same "deficits."

THE GRANDEUR To feel the romance and inspiration of reading and research, leave the computer behind and enter the magical atmosphere of the Rose Reading Room at the New York Public Library.

TRAVELVIEW / SHUTTERSTOCK

Our fractured attention spans are having a clear impact on the way our memory and cognition function, they write. The more we go to Google—or anywhere on the internet—the less likely we are to remember the facts we seek to retrieve. Instead, we remember only where these facts can be found, and consequently become more reliant on the internet for basic recall. Such internet-induced erosions of memory have baleful effects on young adults, the researchers write. They impact the development of a brain region associated with the formation of long-term memory. Come to think of it, I have grown mentally itchy and restless ever since I started Googling things.

As that kid in Iowa City, I was able to plunge deep into books and read for hours on end. But since Google entered my life in my early 30s, I only sink into immersive reading when I travel. Once I'm back on land, and open my laptop, I feel my concentration begin to scatter.

Even as I write this article, following link after link, I feel my memory shrink as it gets outsourced to dozens of tabs in my browser, each offering some new bit of insight I can jam into this text, each promising some twinkling little reward, some key that unlocks my thoughts and gives them language. And though the possibilities of such digital wanderings are mathematically infinite, each new tab makes me feel more isolated, more at sea drifting farther from my goal, in need of some human rescue.

WHAT SORT OF APPLE *did Eve eat? Why is black the color of mourning? What is the origin of the safety pin? When were chairs developed? How much is a human body worth? Does anyone hold a copyright on the bible?*

Each day, Google processes 8.5 billion queries, slightly more than one for every person on Earth.

Those are some of the questions put to the reference desk of the New York Public Library since it opened in 1895—precisely the kind of minutiae we type into the search bar. They are collected in two books—*The Book of Answers* of 1990 and *Peculiar Questions and Practical Answers* of 2019—that also encompass the responses the 12-member reference staff were able to draft. Their answers—from 1895 through to today—usually arrive with a bibliography of works consulted and are often composed with witty personal touches.

"What does it mean if I am being chased by an elephant?" asked one library patron in 1947. "We're going to assume this is a dream and, unless you correct us, we will continue assuming, so as we do not even wish to contemplate what it would mean to be chased by an animal 30 times our size with size 40 (U.S.) feet."

For most of the last century, patrons' questions were asked verbally and recorded on hand- or type-written notecards. In 1968, a telephone line working from 9 to 6, Monday through Saturday, was added. You leave your question, and the librarians root out an answer from among the library's 54 million holdings and call you back, usually within about two weeks. The reference desk hasn't gone anywhere. All told, about 200 queries (you can use email now) pass through the library on any given day—a figure that hasn't flagged since the advent of Google Search, an NYPL librarian informed me when I called.

Why would anyone bother with a librarian when questions are easily answered by a search engine and without the wait? I got my answer earlier this year when I met Nancy Burvant at the Mid-City branch of my new hometown library in New Orleans, where she works as the head of electronic resources.

The midmorning sunlight streamed through the two-story vaulted glass windows at the front of the iconic mid century modern building, illuminating a display for Black History Month. In a city that is 60 percent Black, merely entering a library offered me a way to encounter what's important to my community that no amount of time on the internet can.

We sat in an alcove off her office above the stacks, where Burvant's voice carried above the reverent library hush. The internet hasn't so much challenged the status of the library in public life, Burvant explained, as it has become yet another resource that librarians help

"There's information," the librarian said to me, "and then there's the right information."

patrons tame and understand. The internet is fine for some things, she said, "but how do you know that you're not getting a lot of junk?"

"There's information," she said, "and then there's the right information."

Burvant didn't ask me to take her word for it. She explained there have been plenty of research articles by library science experts on how the internet stacks up against a good reference librarian. The verdict: If you're looking to ground yourself in a topic with fact-based research, librarians are still your best friends.

The digital shift that has crept through libraries over the past 30 years or so has cost millions of dollars in equipment and new media acquisitions and required new forms of training that go beyond the traditional Master of Library Science degree. New Orleanians have been keen to embrace the advances. In 2021, local voters—who are famous for voting down tax renewals—went against character to preserve $17 million in yearly funding to the library.

The infrastructure librarians now navigate is different than the one that shaped the civic-minded explosion of public libraries during the early 20th century. Gone are the massive card catalogs that dominated the entry halls of the libraries I grew up with, replaced by slim terminals feeding into tentacular electronic library management systems. These, in turn, often feed web-based systems such as WorldCat, which can locate any book in almost any library pretty much anywhere. Part of me mourns the tactile experience that began my past inquiries—the holy smell of the wooden drawers, the cards smudged by years of curiosity, the inscrutable, punctuated numerology of the Dewey Decimal System. But their absence, Burvant noted, has made way for other things—space for classes and author readings, PC terminals and media labs, study rooms for tutoring sessions, offices for tech support, and, overall, more places for the public to just *be*.

The library now exists as much in digital space as it does in cement, steel, and—in the case of the Mid-City branch—marble. As Burvant led me through the suite of free phone apps the library offers, I felt like a bit of a dupe for shelling out for iTunes, Netflix, and YouTube. That also goes for eBooks and audio books, of which the library has about 200,000 holdings. And when I check out an online book from the library, Burvant assured me, none of my choices here are spied on. At best, my hold on an item might trigger her colleague Rel Farrar, head of adult acquisitions, to order more copies of what I am looking for.

The fact that eBooks can only be read by one patron at a time puts me back in an approximation of a public space. It reminds me that there is another human being somewhere in this city who shares a curiosity with me. We may never meet, but as I place a hold on the material we're both interested in, I am acknowledging some sort of physical finitude—a democratic compact to share a limited resource. This is not a typical digital experience where the world—and our searches—are available for a price.

But it also presents a tension between the library as a public space and the library as a mere purveyor of digital information like so many others available to us through the search bar. "Libraries have to maintain a balance between the benefits of digitization with the preservation of traditional library values," Burvant said. "The negative side is that people might eventually stop coming to the library altogether, as libraries continue to contribute to the screen-centric culture."

Another risk of digitalization is that it can leave some patrons behind if they don't have access to tech. "Let's not forget the Digital Divide, which can limit the inclusivity of library services and hinder some individuals from fully participating in the library's mission," Burvant said.

Digitalization has other big costs as well. Offering eBooks and audiobooks, said Burvant's colleague Farrar, constituted some of the library system's biggest expenses. That's because they can't be purchased once and forever like a book can. Instead, libraries are forced by publishers to buy a sort of periodic license to offer eBooks in their collections. These licenses have to be renewed every couple of years, and they are not cheap. For instance, 90 eBook and audiobook versions of the best-selling Britney Spears memoir, *The Woman in Me*, costs the library $6,000 to keep in stock. When the license lapses in two years, the library will have to shell out another $6,000 if Farrar elects to keep all 90 copies available. By contrast, 30 copies of the print edition cost the library only $600.

"Ten years ago, to spend $1,000 on a book meant it had to be one of the biggest books of the year," Farrar said. "Now there are multiple eBooks every year that we spend thousands of dollars on each." It's not an accident that the bulk of the New Orleans library's collection still resides in the million or so print resources it houses. It's this collection of printed, physical books, for me, that still gives the local library its gravitational pull.

Besides, there is still nothing like that space between asking and finding out, that period of enforced contemplation between question and answer. Traversing the space between the two allows me to take a physical journey into my community, which, wherever I find myself, always has the power to surprise me.

One recent Saturday afternoon, I dropped by the hulking mid-century aquarium of the New Orleans Public Library's main branch, a few miles from the branch where I met Burvant, to return J.M. Coetzee's *The Pole*—a novel by the South African Nobel laureate I'd previously been unaware of before spotting it on a library display. And, as it often is on the weekends, the library was a model of the vibrant, integrated city New Orleans wishes to be.

None of the self-reinforcing tribal divisions that the internet seems so keen to foist upon us were visible. Affluent-looking young mothers parked their strollers at a catalog terminal in front of a pair of homeless men playing chess at a table. Back in the media lab, a group of high school boys in puffy jackets and sneakers were recording a do-it-yourself rap video while a middle-aged guy in a fishing cap and muddy galoshes inquired at the circulation desk about an upcoming genealogy seminar the library is hosting. Other patrons were situated throughout the vast atrium's armchairs just doing whatever and enjoying the communal space. Old men read newspapers, students crammed for tests, a daughter taught her mother how to file her taxes online. On this Saturday afternoon, they were here together as one people, each drawn by some search query of their own.

What might have been lost if they had just Googled it?

CHARLES DIGGES is an environmental journalist and researcher who edits Bellona.org, the website of the Norwegian environmental group Bellona.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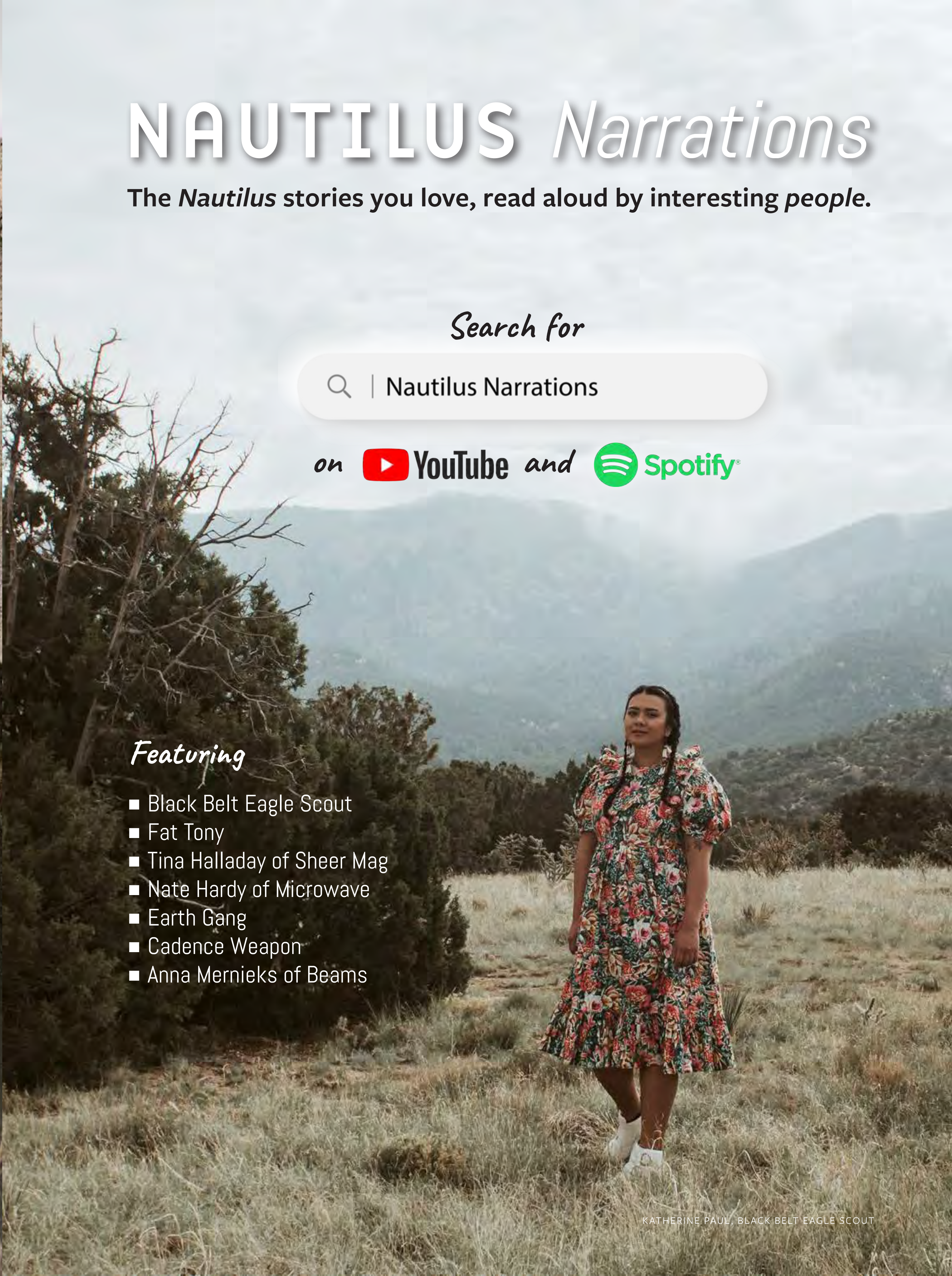
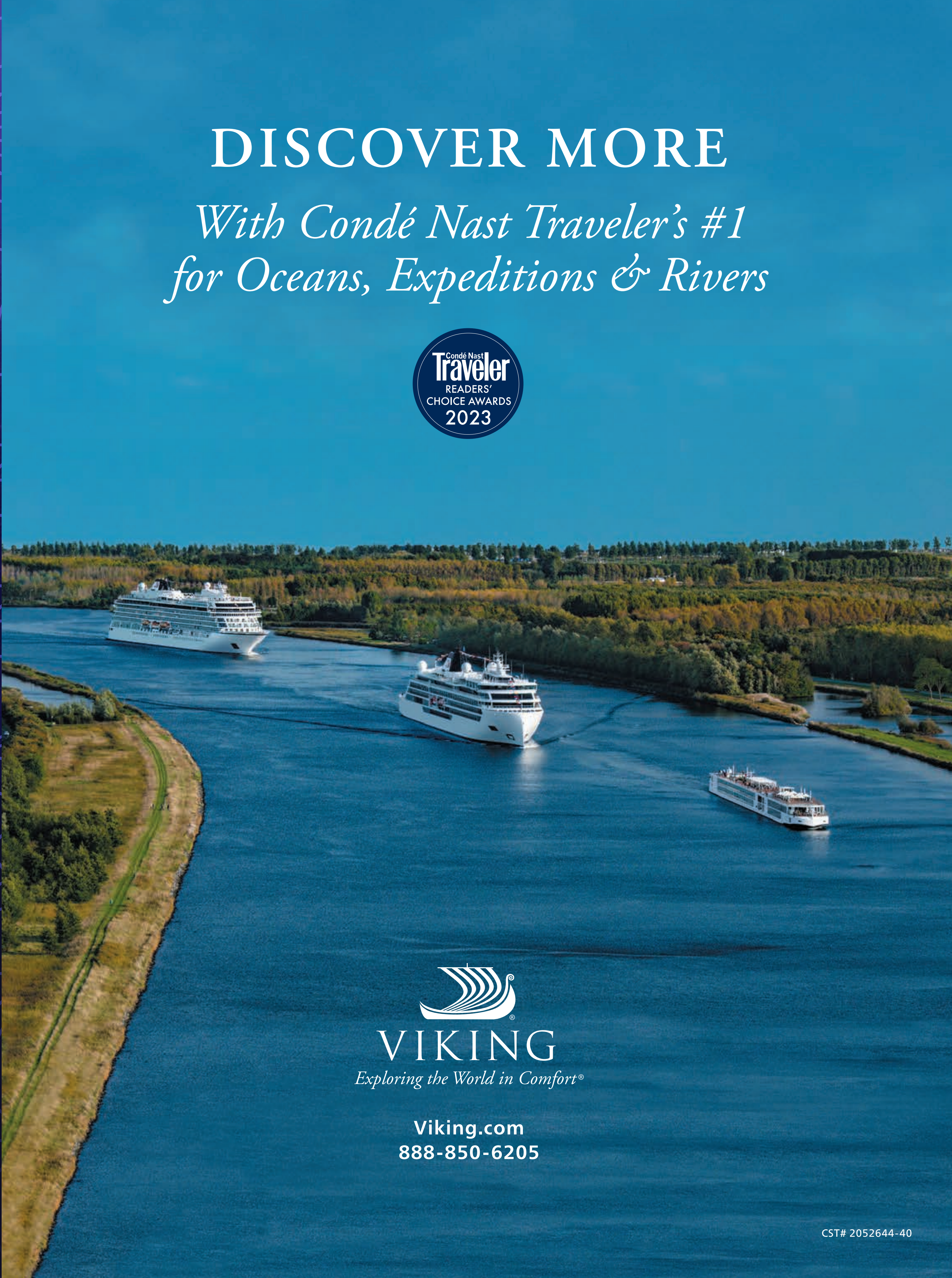


KATHERINE PAUL, BLACK BELT EAGLE SCOUT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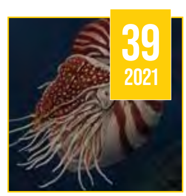

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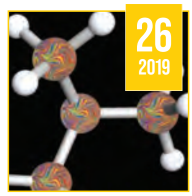
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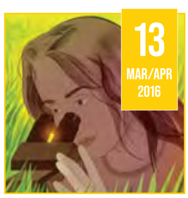
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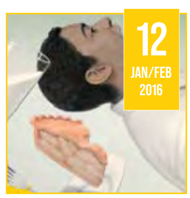
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MY 3 GREATEST REVELATIONS

Archaeology at the Bottom of the Sea

David Gibbins on his 3 greatest revelations while writing
A History of the World in Twelve Shipwrecks

BY DAVID GIBBINS

David Gibbins, age 23, during the 1985 excavation of a Roman cargo ship off the coast of Siciliy, Italy. *Credit: Jim Coates; courtesy of St. Martin's Press.*

1 ARCHAEOLOGY HAS MORE APPLICATION TO RECENT HISTORY THAN I THOUGHT

Early on in my career, I had a traditional view of archaeology—excavation was about uncovering artifacts that gave insights into periods for which other types of evidence were limited, generally meaning the older the site the more worthwhile it was to investigate. For two decades that approach guided my research into trade in the ancient Mediterranean and my excavations of shipwrecks containing pottery amphoras, important registers of economic activity in the Greek and Roman periods. But since then, I have focused on sites of more recent historic date—from 16th-century wrecks off England to ships of the 19th century in the Great Lakes—and have found my perspective changing.

I realized that documentary evidence for ships even of the 19th century is often minimal, and that wrecks of any date can produce unique finds. Who would have thought, for example, that a World War II wreck nearly 4,700 meters deep in the Atlantic would contain a cache of letters so well-preserved that they could still be read, opening up a whole new vista on people's lives and aspirations at a time when the future of the world hung in the balance. I realized that there is no cutoff point after which archaeology ceases to be meaningful, even for sites that are only just out of living memory.

2 ARCHAEOLOGICAL PROJECTS ARE OPEN-ENDED

I was struck by how many excavations remain active projects years later as a result of advances in archaeological science. Blocks of metal called ingots from the Uluburun Bronze Age wreck off Turkey, which was excavated between 1984 and 1994, were subject to trace element analysis decades later, which has led to a fresh view of trade networks in early prehistory.

Recent analysis of bones from King William Island in the Canadian Arctic has provided compelling evidence that the men of Sir John Franklin's lost expedition resorted to cannibalism. These breakthroughs were possible due to techniques and refinements of analysis that were not available—and might not necessarily have been anticipated—when the initial excavations were completed. It's a great argument in favor of retaining artifacts and other materials from excavations for future scientific investigation.

3 ARCHAEOLOGY IS NOT A HARD SCIENCE

One thing that makes shipwrecks so worthy of study is the extremely high "resolution" of the data: Each shipwreck reflects a single event of loss in which the artifacts were not deliberately discarded, but were in use at the time.

Highly datable artifacts, such as coins or pottery, can often be used to closely date other objects in the assemblage, which may offer clues to their significance in research areas far removed from the "maritime."

In my book, I found myself writing about the philosophy of Plato, the medieval libraries of Baghdad, Norse walrus hunters in the Arctic, King Henry VIII's music, Charles Darwin's fixation on barnacles, and the aspirations of a radio student in India in World War II. I allowed myself to be led by what I happened to find fascinating rather than by a formulaic approach to each site. Thus unshackled, the narrative becomes a reflection of my life-experience as much as anything else.


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MAKING HUMANS AQUATIC