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Life as We Don't Know It

How to search for aliens that are nothing like Earthlings

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VOLUME 328, NUMBER 2

SCIENTIFIC AMERICAN

ON THE COVER

Astronomers tend to search for extraterrestrial life that resembles our own—beings that require liquid water, breathe oxygen and use DNA—partly because those are the easiest types of life to seek. But some scientists are searching for life that is so different from Earth biology that we might have trouble recognizing it. Researchers are developing new strategies for identifying life as we don't know it. **Illustration by William Hand.**

Photograph by Aubrey M. Kelly

SCIENTIFIC AMERICAN


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Marley Allen-Ash


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FROM THE EDITOR

Laura Helmuth is editor in chief of *Scientific American.*
Follow her on Twitter @laurahelmuth

Mates and Strangers

Every once in a while we publish a story that makes the editorial team at *Scientific American* melt. When we were reviewing illustrations for "The Neurobiology of Love" about pair-bonding in prairie voles, the most common response was, "Aww." First of all, they're so stinking cute. Unlike promiscuous species like meadow voles, they pair up for life, raise young together and cuddle for comfort. For about 50 years they've been the go-to animal model for studying attachment and relationships and what looks like some rudimentary version of love. On page 40, scientists Steven Phelps, Zoe Donaldson and Dev Manoli explain how we've learned so much about commitment from prairie voles. Some free advice: date all the meadow voles you like but marry a prairie vole.

Our cover story this month is about one of the most mind-bending searches in science: the attempt to find life as we don't know it. (Science writer Sarah Scoles on page 32 proposes the acronym "LAWDKI" for this search.) How do you look for aliens that are profoundly alien to Earthlings? Scientists are figuring out how to scan for life that uses different varieties of DNA or RNA or that doesn't use genetic sequences at all. Depending on how you define "life," it could encompass completely different chemistry from our own or molecules that assemble themselves.

Astronomers are worried that swarms of satellites are interfering with Earth-based observatories. Increasing numbers of Starlink and other telecommunications satellites zip through low-Earth orbit and are visible with the naked eye. Until now, they've been exempt from environmental reviews, but a recent U.S. Government Accountability Office report suggests they could come under closer regulation. Journalist Rebecca Boyle on page 46 quotes an astronomer posing a "deeper cultural question" about how much power satellite companies should have: "Should Elon Musk control what people see in the night sky?"

Actor Alan Alda is a great advocate for science communication, and he goes way back with *Scientific American:* he hosted a TV series with us from 1993 to 2007 called *Scientific American Frontiers*. Now he's generously sharing his own experience with Parkinson's disease to help others recognize what can be one of the earliest signs of the disease, called REM sleep behavior disorder (RBD). People with the condition act out their dreams, which can be dangerous to them and their partners. On page 56, science writer Diana Kwon shows how RBD predicts neurodegenerative disease and could give patients an early start on treatments or clinical trials.

The term "positive feedback" sounds like it ought to refer to something nice, right? As climate communicator Susan Joy Hassol discusses on page 64, the language that scientists use to describe potentially catastrophic self-reinforcing cycles (that is, positive feedback) and other aspects of climate change can mislead people about the urgency of the crisis. She points out the unintended meanings of common terms and suggests much snappier and clearer alternatives. Enjoy the chalkboard that begins the article.

Some of the biggest contributors to the climate emergency are the production and use of cement and concrete, which account for about 9 percent of global carbon dioxide emissions. It doesn't have to be this way. On page 52, *Scientific American*'s senior sustainability editor, Mark Fischetti, presents a 12-point plan for how to improve manufacturing and minimize cement's climate impact. The wonderful graphics by illustrator and designer Nick Bockelman will make you get out your childhood dump trucks. We need all the solutions we can get. SA

Illustration by Nick Higgins

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UNDERMINING REALITY

“Understanding Gaslighting,” by Paige L. Sweet, really hit home for me. I’m a severely disabled man who must use a wheelchair. I’ve endured for decades the humility of being marginalized and the abuse and neglect of the disability system. Yet when I’ve spoken about these injustices, I’ve been told that I’m “bitter,” lying or in need of psychological help. Like some of the people Sweet mentions in her article, I’ve questioned the morality of my character as well as my sanity.

It’s very important to educate people about the nefarious practice of gaslighting. If I had known that I was being gaslighted, then I think I would have been more effective in countering it.

JOSEPH JAGELLA *via e-mail*

I have a much better picture in my mind of what gaslighting is now. After finishing the article, I couldn’t help but think back to the U.S. Senate hearings on the confirmation of Clarence Thomas to the Supreme Court and the grilling of Professor Anita Hill.

JAMES P. NELSON *via e-mail*

Sweet provides a concise, important description of what gaslighting is and how it is being studied—a most timely endeavor. The research she describes seems poised to further our understanding of the harm done by brainwashing or what some professionals call “undue influence.” Both use similar methods: power, influence and control. Perhaps the more the broader population understands gaslighting and brainwashing, the less often we will let folks get away with them.

AUDREY N. GLICKMAN *Pittsburgh, Pa.*

NATURAL CITY

In “Cities Build Better Biologists” [Forum], Nyeema C. Harris argues that the experience of living in an urban area can be just as relevant to the training of young biologists as living in a rural one. She goes on to say that we should reframe urban areas as valuable for their biodiversity and unconventional ecology.

I agree and would invite readers—especially nonscientists—to follow up on her message with action. I can think of two ways urbanites can be more attentive to nature in the big city: First, anyone can act as a “citizen scientist” using the mobile app iNaturalist. Your documented observations, verified by experts, contribute to the tracking of biodiversity in your hometown. Second, growing native species of plants—if you have any open land available to you—attracts pollinators, birds and other animals. Even in a heavily urbanized area, you can appreciate and support the natural world around you.

ZACHARY EPSTEIN *Houston, Tex.*

GASLIGHT ON THE PAST

In “See More” [From the Editor], Laura Helmuth mentions that the term “gaslighting” originated in a 1930s play that subsequently became a film starring Ingrid Bergman as a victim of this type of psychological manipulation. In citing the Bergman vehicle alone, she unwittingly enabled an alleged past attempt at gaslighting.

The first film version of *Gaslight* was released in 1940, directed by Thorold Dickinson and starring Anton Walbrook as the murderous and venal sociopath and Diana Wynyard as his deeply abused wife. It was a British production with cast and crew largely unfamiliar to American audiences. Four years later MGM put out its own version, featuring a well-known director (George Cukor) and a big-name starring cast (Bergman, Charles Boyer, Joseph Cotten, Dame May Whitty and the then teenage Angela Lansbury). Among strategies to ensure the latter film’s commercial success, MGM engaged in an effort to destroy as many extant copies of the 1940 version as possible and to pretend as if the previous film had never existed.

That effort was not wholly successful. Copies of the 1940 version survived, and it has been viewed in various venues, including TCM from time to time. Both versions are excellent and should be seen by any serious cinephile, but the 1940 version is considered to hew closer to the original stage play, entitled *Gas Light,* by Patrick Hamilton (author of *Rope*). The 1940 version also has a haunting score missing from its successor.

MAC BRACHMAN *Chicago*

SCHOOLS AND CHILDHOOD HEALTH

Thank you for featuring the two articles in the September 2022 issue about the state of both physical and mental health in today’s youth and what schools can do to address those problems: “Health Care Starts at School,” by the Editors [Science Agenda], and “Protecting Kids’ Mental Health,” by Mitch Prinstein and Kathleen A. Ethier [Forum].

One of the major sources of poor mental health and school achievement is childhood poverty. This is what makes both stories so depressing. We need better supports for families with children so that they can focus on school rather than on the stressors that result from poverty. As described in the Science Agenda story, the amount Congress allocated to expand school health centers in 2021 ($5 million) is paltry in comparison with the need.

Prinstein and Ethier’s description of mental health programs for schools in their Forum piece is certainly encouraging, but this approach will also need many more resources for schools than we currently allocate.

I wish there were a magic wand that we could wave in schools to overcome both mental and physical health problems, but a lot of the problems derive from socioeconomic sources that schools alone cannot solve on their own.

DAN ROMER *Bryn Mawr, Pa.*

CLARIFICATION

"Artificial Confidence," by Gary Marcus, noted that an AI released in May 2022 by Google "couldn't tell the difference between an astronaut riding a horse and a horse riding an astronaut" and referred to accompanying images showing astronauts riding horses. Google's AI Imagen did not compare these images with others. Rather, when researchers prompted Imagen to create images of "A horse riding an astronaut," the AI created only images of astronauts riding horses.

ERRATA

"Healing Waters," by Stephanie Stone [August 2022], incorrectly described Jose Jimeno as a virologist at PharmaMar. He is an oncologist and medical director of PharmaMar's virology unit.

"Testing Nukes," by Adam Mann and Alastair Philip Wiper, incorrectly listed plutonium as being among the substances used to generate a fusion reaction at the National Ignition Facility. The facility conducts other experiments involving plutonium.

"Name Check," by Rebecca Dzombak [Advances; November 2022], should have said the database of dolphin whistles included nearly 1,000 recording sessions, not nearly 1,000 recorded whistles.

"COVID Relay," by Megha Satyanarayana [Advances; November 2022], ran a graphic depicting the number of COVID cases reported in each species in a database as of September 6, 2022. It was missing the Sumatran tiger, a subspecies with two reported cases in the database at that time.

"An Invisible Epidemic," by Elizabeth Svoboda [December 2022], included repeated and missing text on page 56 of the U.S. print edition. The correct version of the article is available at www.scientificamerican.com/article/moral-injury-is-an-invisible-epidemic-that-affects-millions

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Let Teenagers Sleep

Despite years of evidence that starting school later promotes better health and improved grades, too few schools have adopted this measure

By the Editors

Teenagers are some of the most sleep-deprived people in the U.S. On average, teens do not get enough sleep, and more important, they do not get enough quality sleep, researchers say. We could blame cell phones and other light-emitting technologies for keeping kids up at night, but late nights are just part of the equation. In addition to technology, one fairly indisputable factor contributes to this collective sleepiness: school start times.

Over decades researchers have amassed evidence showing that pushing back the first bell of middle and high school would benefit the physical, mental and emotional health of older children, not to mention their academic performance. The Centers for Disease Control and Prevention, along with several medical societies, has endorsed later start times. Some school districts, as well as the state of California, have already shown respect for that evidence with new start times.

Yet far too many school districts are reluctant to make the change, whether for logistical, financial or cultural reasons. This is unfair to teens. A generation of students is playing catchup from COVID, and we need to prioritize their health and wellness by pushing back the start of the school day. Honoring their biological and social needs will create more resilient adults who can thrive in a world filled with current complexities and future ones we can't begin to predict.

Teenagers need about nine hours of sleep a night—but they get closer to seven. And around puberty, their circadian clocks shift by a couple of hours, meaning they get tired later at night than before and wake up later in the morning than they used to. This shift reverses at adulthood. The biological nature of this daily rhythm means that sending a teenager to bed earlier won't necessarily mean they fall asleep earlier.

Experts tell us that teens are missing out on both restorative sleep and REM sleep, especially the cycles that normally happen just before a person wakes up. Restorative sleep helps to repair the body after a hard day, and it may improve immune function and other biological processes. REM sleep solidifies events and learning into memories [see more about sleep cycles in "When Dreams Foreshadow Brain Disease," on page 56]. So when a 10th grader who naturally goes to bed around 11 P.M. has to wake

Illustration by Thomas Fuchs

up at 6 A.M. for school, that teen is losing not only hours of sleep but hours of quality sleep. And even if they sleep in on the weekends, they won't fully catch up.

These kids are telling us they need more sleep. In survey after survey, they say when school starts later, they are not as tired all day, they tend to get to school on time, and they are less likely to have to be nagged to get out of bed. They tell us that as their sleep time decreases, their use of tobacco and drugs increases, including drugs that could help them stay awake. They tell us that getting one less hour of sleep a day leaves them feeling hopeless and, sometimes, suicidal. Research has shown that suicide risk in children increases during the school year, and sleep deprivation could be a contributing factor. Other studies show that getting one less hour of sleep a day is associated with weight gain. Researchers have told us that sleepy teens are more prone to car crashes and that even 30 minutes of extra sleep would help alleviate some mental health concerns. Even teachers have reported that with later start times, their students are more engaged in the morning, and teachers themselves are more rested.

Despite decades of research, thousands of publications and clear science, schools in only a few states and the District of Columbia have pushed their start times to 8:30 A.M. on average, which researchers say is a compromise—a better time would be closer to 9 A.M.

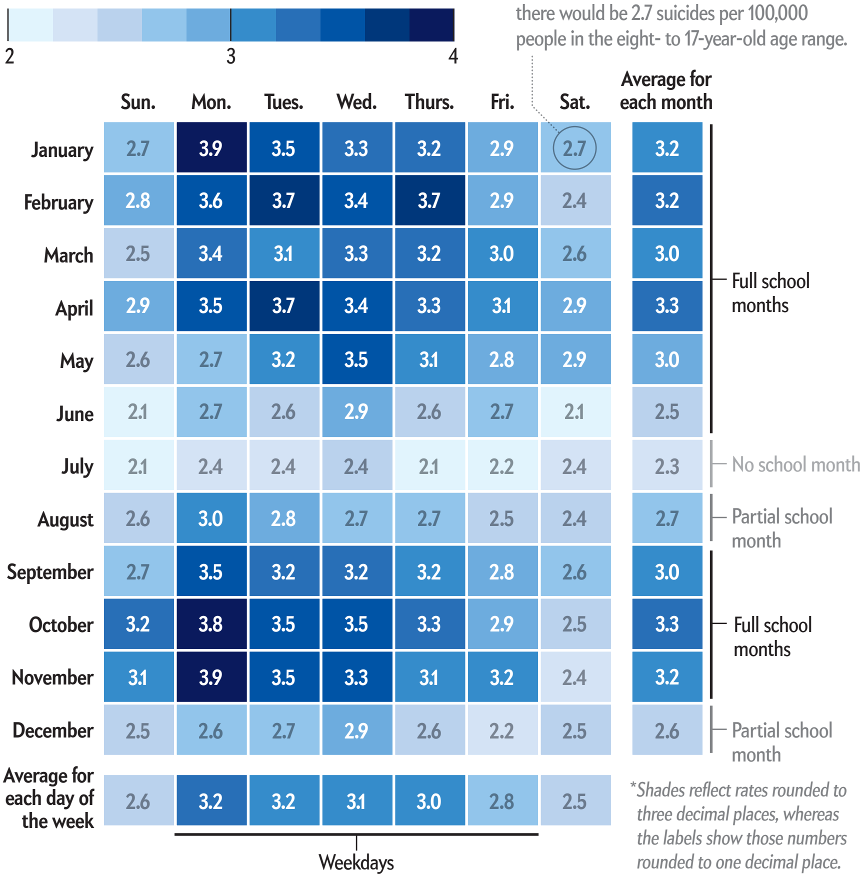
The path to delayed school start times is riddled with potholes. Bus schedules have to change. Teacher and administrator schedules have to be altered. After-school sports and enrichment programs might have to begin later. Parents and caretakers with more than one child may have to juggle child care for older children to get the younger ones to their earlier start times. A delayed school start could also mean adults with inflexible work schedules are late for work.

Experts say our agrarian model of education was designed to get teens up early and home before dark to tend to the farm, but it is no longer relevant for most modern students. Our cultural views of teens as lazy and of needing sleep as a weakness are harmful and inaccurate. And our grumbling that if *we* survived early start times, today's teens can, too, is callous and dismissive of science.

Suicide Rates Increase during the School Year

Shade of blue shows suicide rate for each day and month* (number of suicides per 100,000 person-years)

This number means that if a year consistently followed the rate of Saturdays in January, there would be 2.7 suicides per 100,000 people in the eight- to 17-year-old age range.



	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Average for each month
January	2.7	3.9	3.5	3.3	3.2	2.9	2.7	3.2
February	2.8	3.6	3.7	3.4	3.7	2.9	2.4	3.2
March	2.5	3.4	3.1	3.3	3.2	3.0	2.6	3.0
April	2.9	3.5	3.7	3.4	3.3	3.1	2.9	3.3
May	2.6	2.7	3.2	3.5	3.1	2.8	2.9	3.0
June	2.1	2.7	2.6	2.9	2.6	2.7	2.1	2.5
July	2.1	2.4	2.4	2.4	2.1	2.2	2.4	2.3
August	2.6	3.0	2.8	2.7	2.7	2.5	2.4	2.7
September	2.7	3.5	3.2	3.2	3.2	2.8	2.6	3.0
October	3.2	3.8	3.5	3.5	3.3	2.9	2.5	3.3
November	3.1	3.9	3.5	3.3	3.1	3.2	2.4	3.2
December	2.5	2.6	2.7	2.9	2.6	2.2	2.5	2.6
Average for each day of the week	2.6	3.2	3.2	3.1	3.0	2.8	2.5	

**Shades reflect rates rounded to three decimal places, whereas the labels show those numbers rounded to one decimal place.*

Data published by the CDC and analyzed by emergency pediatric psychiatrist Tyler Black show a clear pattern: children die by suicide at much higher rates on school days than they do on weekends or during summer months. This graphic, originally entitled "Suicide Rates by Month and Day, Ages 8–17, 2000–2020," appeared in the online *Scientific American* article "Children's Risk of Suicide Increases on School Days," written by Black. Like many of his peers in pediatric medicine, he calls for later school start times, among other measures, to help improve kids' mental health.

Source: CDC Wonder, Centers for Disease Control and Prevention; Data analysis by Tyler Black

Access to education is a basic right in the U.S. But it's time to stop thinking of school start times as immovable mountains. While more states ponder start time legislation, school district administrators should prioritize it, and people running for school boards need to add start times to their platforms. State-level funding agencies have to clear hurdles for districts wanting to try this. Employers need to be more flexible to help parents adjust to school schedules, especially with hourly employees. And the unions that represent teachers and other education professionals need to negotiate with teens also in mind.

For decades we've ignored the overwhelming evidence that delayed start times help teens succeed. Let teenagers sleep. There is nothing "woke" about that. SA

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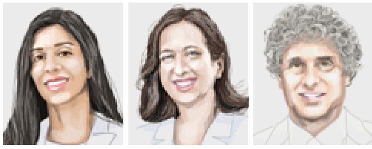
Graphic by Amanda Montañez



Sapna Cheryan teaches psychology at the University of Washington. **Allison Master** teaches education at the University of Houston. **Andrew Meltzoff** co-directs the Institute for Learning & Brain Sciences.

Computer Science and Engineering Need Women

Tech culture and stereotypes dissuade them

By Sapna Cheryan, Allison Master and Andrew Meltzoff

Only 20 percent of computer science and 22 percent of engineering undergraduate degrees in the U.S. go to women. Women are missing out on lucrative, high-status careers, and society is missing out on the contributions they might make to these fields. For example, women might improve smartphone conversational agents so that they are able to suggest help not only for heart attack symptoms but for indicators of domestic violence.

Why are so few women entering these fields? A common explanation is that they are less interested than men in computer science and engineering. Though technically accurate, this explanation is incomplete and worsens the very disparities it seeks to explain. Focusing on interest suggests it is the girls and women who need to change. We think changing the male-oriented cultures of the fields will draw in more young women.

Young children and adolescents in the U.S. believe girls are less interested than boys in computer science and engineering. And girls who strongly endorse such stereotypes show the least interest. How do these gender stereotypes become self-fulfilling prophecies?

We found that girls are significantly less likely to choose a computer science activity after hearing that girls are less interested in it than boys are. The message convinces them they won't be interested in the activity—and changes their behavior. Noting differences in interest without giving the broader context of *why* these differences exist can contribute to girls' underrepresentation.

One reason for girls' lower interest in these fields is their male-oriented imagery and cultures. When asked to describe computer scientists, for instance, American students often imagine white and sometimes Asian male geniuses who are socially awkward, play video games and like science fiction. Experiments we conducted with college and high school students show that these preconceptions can have profound effects.

We investigated how salient images in classrooms affect young women's interest in computer science by showing them images either more or less stereotypically associated with men (for example, *Star Trek* posters versus nature posters). When their classroom did not reflect these stereotypes, young women expressed increased interest in computer science. Men and boys, in contrast, did not shift their interest as strongly in response to the different images.

Many computer scientists and engineers do not fit the stereotypes, but until those depictions are diversified, we may keep seeing more women than men feeling they don't belong in these fields. We have documented that computer science and engineering have "masculine defaults." These features reward or value behaviors commonly associated with being a man, such as self-promotion and hypercompetitiveness. At Google, women were getting promoted less often than equally qualified men because of a policy that required putting oneself up for promotion. This policy was biased because women in the U.S. tend to be socialized not to self-promote and may even receive social and economic backlash when they do.

History and context also matter. Before the rise of modern computer science stereotypes, women received a significantly higher proportion of undergraduate computer science degrees—37 percent in 1984, compared with 20 percent in 2018. Women are most likely to pursue computer science in countries with less male-oriented computer science imagery (such as Malaysia).

Rather than blaming women and girls for their current lower interest, we should focus on what society can do to create more welcoming cultures. Strategies could include elevating norms and traits that are not stereotypically masculine. For example, companies could further increase rewards for promoting others' achievements and working toward collective goals. Universities could implement more inviting pathways into computer science that do not require prior programming experience, as done at Harvey Mudd College. Popular media could more often promote images of computer scientists who do not fit traditional male-oriented stereotypes.

The need for more welcoming cultures is a systemic problem, and creating them is the responsibility of the tech industry and society more broadly. We have to articulate the role that the perceived and actual cultures of these fields play in generating these patterns. Without that change, it will be hard to make tech more inclusive of our entire population.

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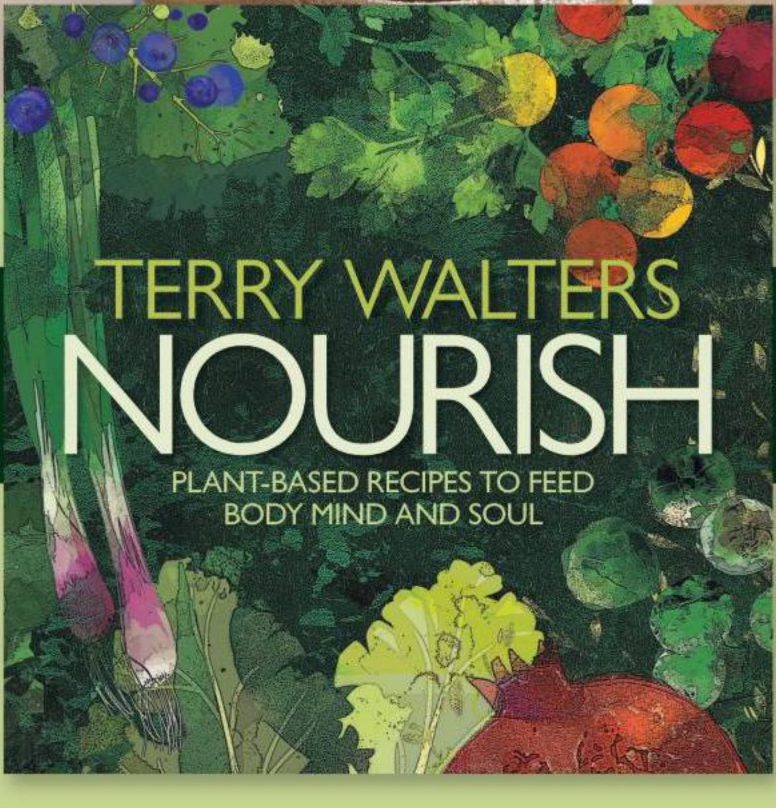
Illustration by Marley Allen-Ash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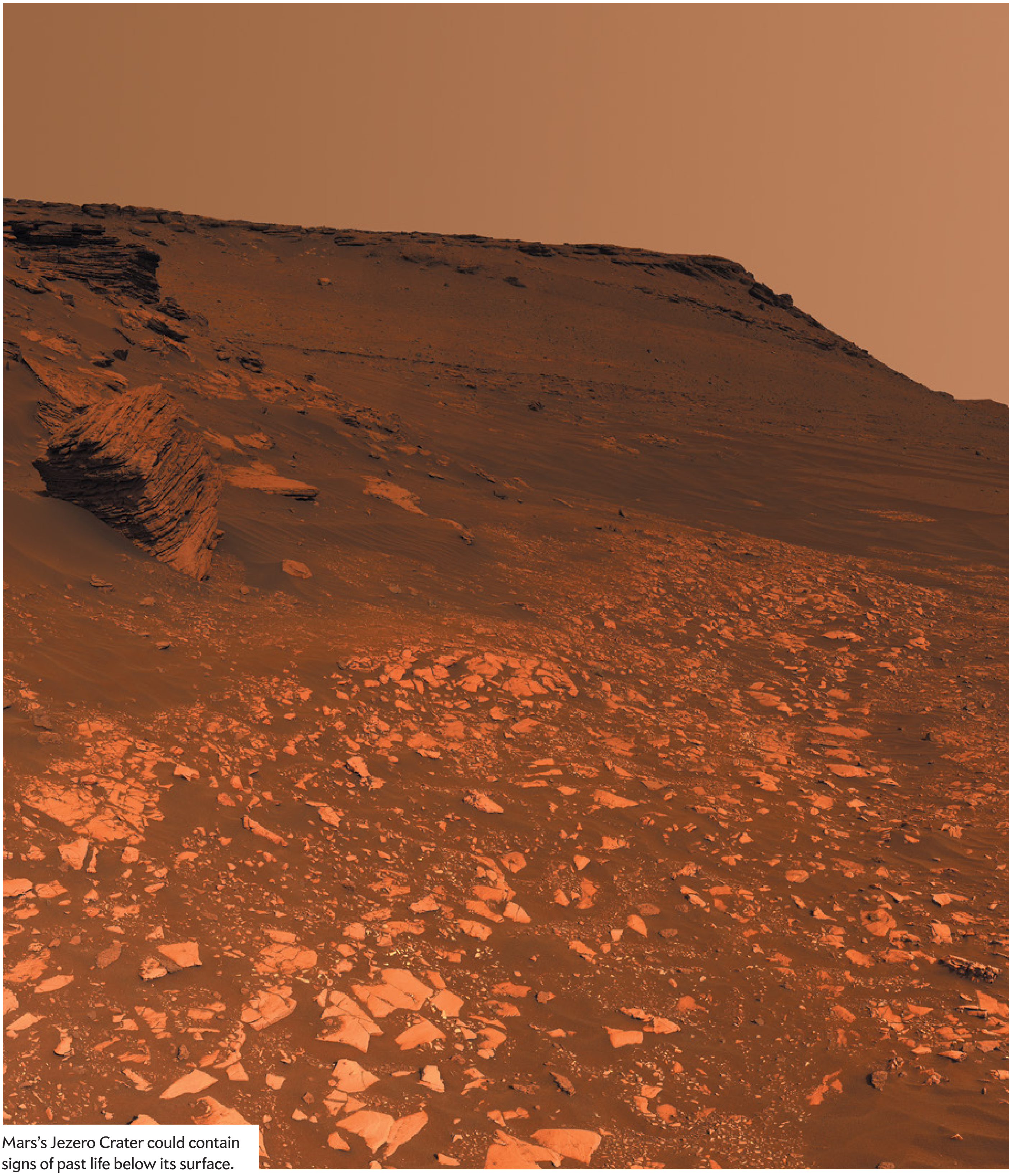

Mars's Jezero Crater could contain signs of past life below its surface.

INSIDE

- A drone scoops rare species from Hawaiian cliffsides
- Colliding planets could explain a mysterious radius gap
- Early plants' plumbing helped them conquer the world
- Evidence suggests large-scale copper mining in North America 6,000 years ago

NASA/JPL-Caltech/ASU/MSSS

EXTRATERRESTRIAL LIFE

Mars's Downfall

Life on Mars may have been its own worst enemy

Although we know early Mars was wetter, warmer and more habitable than today's freeze-dried desert world, researchers have yet to find direct proof that life ever graced its surface. If such life did exist, however, as a new study suggests, it could have helped tip the planet into its current inhospitable state. The findings further identify certain regions of Mars—including Jezero Crater, where NASA's Perseverance rover now roams—as most likely to host signs of this past life.

Re-creating Mars as it was four billion years ago using climate and terrain models, researchers concluded methane-producing microbes could once have thrived mere centimeters below much of the Red Planet's surface, consuming atmospheric hydrogen and carbon dioxide while protected by overlying sediment. But that buried biosphere would have ultimately retreated deeper into the planet, driven by freezing temperatures of its own making—perhaps to its doom. Their study, published in *Nature Astronomy*, proposes that the interchange among hydrogen, carbon dioxide and methane (all heat-trapping greenhouse gases) would have triggered global cooling that covered most of Mars's surface with inhospitable ice.

"Basically what we say is that life, when it appears on the planet and in the right condition, might be self-destructive," says study lead author Boris Sauterey, a postdoctoral fellow at Sorbonne University. "It's that self-destructive tendency which might be limiting the ability of life to emerge widely in the universe."

In 1965 the late chemist and ecologist James Lovelock—then a researcher at NASA's Jet Propulsion Laboratory—argued that certain chemical compounds in an atmosphere act as biosignatures indicating life's presence on another world. On Earth, for instance, the coexistence of methane (from methane-producing bacteria, called methanogens) with oxygen (from photosynthetic organisms) constitutes a potent biosignature: each gas eradicates the other in ambient conditions, so the persistence of both indicates a steady replenishment most easily explained by biological sources. Lovelock's work forms the basis of today's scientific search for alien life. It also informs the Gaia hypothesis, which he codified with biologist Lynn Margulis during the 1970s. This hypothesis, named after a "Mother Earth" deity from Greek mythology, suggests that life is *self-regulating:* Earth's organisms collectively interact with their surroundings in a way that maintains environmental habitability. For instance, higher global temperatures from excess atmospheric carbon dioxide also boost plant growth, which in turn siphons more of the greenhouse gas from the air, eventually returning the planet to a cooler state.

In 2009 University of Washington paleontologist Peter Ward put forward a less optimistic view. At planetary scales, Ward argued, life is more self-destructive than self-regulating and eventually wipes itself out. In contrast to the Gaia hypothesis, he named his idea after another figure from Greek mythology: Medea, a mother who kills her own children. To support his "Medea hypothesis," Ward cited several past mass extinction events on Earth that suggest life has an inherently self-destructive nature. During the Great Oxidation Event more than two billion years ago, for instance, photosynthetic cyanobacteria pumped huge amounts of the gas into Earth's oxygen-starved atmosphere. This eradicated the earlier dominant life-forms: methanogens and other anaerobic organisms for which oxygen was toxic. "You just look back at Earth's history, and you see periods where life was its own worst enemy," says Ward, who was not involved in the new study. "And I think this certainly could've been the case on Mars."

On Earth, though, the flood of oxygen also proved crucial for biological diversification and the eventual emergence of our biosphere's multicellular ancestors—showing that defining a situation as Gaian or Medean might be a matter of perspective. Until life is found on other worlds, however, we are left to examine the question through theoretical studies such as Sauterey's.

Kaveh Pahlevan, a research scientist at the SETI Institute, who was not involved in the study, says that the work "does broaden the way we think about the effects that biospheres can have on habitability." But he notes that it considers only the planet-altering effects of one metabolism type. The study would not capture the intricacy of something akin to the Great

TECH

A Daring Collection

Flying robots scoop up rare plants from inaccessible places

On a knife-edge ridge on the Hawaiian island of Kauai, a delicate plant with a tuft of yellow flowers sprouts from the rock. The only sounds are the wind, the murmur of waves far below—and the hum of a drone. That drone carries a suspended robotic arm stabilized with its own propellers, which slices through the plant's stem before gently lifting it away. As the tiny *Schiedea* specimen's leaves flutter in the air, the drone descends and delivers it directly to researchers waiting below.

This scene—repeated dozens of times with various species as part of a new study—shows how drones can help scientists pluck rare and endangered plants from spots that would otherwise be dangerous, if not impossible, for humans to reach. "It's a fabulous development and use of technology to get a lot more infor-

Mamba lifts a sample of *Wilkesia hobdyi.*

Ben Nyberg/National Tropical Botanical Garden

Oxidation Event, which hinged on the conflicting influences of methanogens and cyanobacteria. Sauterey acknowledges this limitation: “You can imagine that a more complex, more diversified [Martian] biosphere would not have had the negative effect on planet habitability that just methanogens would have had,” he says. The study highlights how a complex ecosystem, like that of early Earth, may be essential to recovery from otherwise catastrophic environmental change.

Beyond life’s potential fate, the study suggests a way to find it: Although the researchers did not explore the possibility of present-day methanogens lurking deep within Mars’s subsurface, they did pinpoint places untouched by ice for large swaths of the planet’s history where such microbes could have once thrived closer to the surface. One spot is Jezero Crater, the current target of the Perseverance rover’s search for biosignature-bearing materials. But it is possible that fossil evidence of early methanogens would be under too much sediment for the rover to reach.

The study also identified two even more promising sites: Mars’s Hellas Planitia and Isidis Planitia regions. These targets fit with a broader rising interest in examining the Martian subsurface for signs of life, says California Institute of Technology geobiologist Victoria Orphan, who was not involved in the study. Sauterey’s research, Orphan says, is “a reference point to help stimulate debates and deeper thinking about future missions.”

Sauterey is careful to point out that the new work is hypothetical—and that just because parts of Mars’s crust were once habitable does not mean the planet was ever inhabited. Whether or not ancient methanogens ever lived on Mars, however, the results of the study illustrate how life itself can set the conditions for its own flourishing—or fizzling—on any world in the cosmos. Even single-celled organisms have the power to transform an otherwise habitable planet into a hostile place. And, Sauterey darkly adds, “with the technological means that we have, humans can do that even faster.” —*Allison Gasparini*

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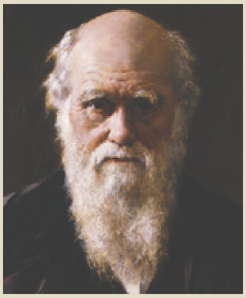
mation than a person trudging around,” says Warren Wagner, a botanist at the Smithsonian Institution. He was not part of the study but is a research associate at the National Tropical Botanical Garden, one of the institutions involved.

The work, described in *Scientific Reports*, builds on decades of botanical investigations of Kauai’s more than 250 native plant species. Historically, botanists have rappelled down the island’s sheer rock faces to grab samples of specific plants that they can raise in a nursery to perpetuate species at risk of extinction. Study co-author Ben Nyberg, a geographer and drone specialist at the National Tropical Botanical Garden, and his team instead used a commercially available drone to heft a separate robotic unit built from scratch named the Mamba. An operator controls the Mamba’s propellers to keep it steady and maneuver it sideways precisely enough to snag each plant.

The Mamba’s sampling components include a foam-padded grasping arm that can move like a wrist and a hook that draws a plant’s stem toward a blade. Next, the team plans to equip the Mamba with other tools, such as a vacuum to suck in plant material or a nozzle to spray a slurry of seeds and growing medium onto a cliffside for replanting.

Similar drone systems could help researchers access other forbidding areas such as the tabletop mountains that jut above the Amazon jungle or the “sky islands” of the southwestern U.S.—isolated mountain ranges rising abruptly from the desert. “Basically this allows users to reach completely inaccessible areas, wherever they may be,” says Nyberg, who is completing a Ph.D. at the University of Copenhagen.

“Many of the rarest and most endangered species found only in Hawaii prefer these cliff habitats, but surveys of their population sizes and collections of seeds have involved great risk to the field biologists skilled enough to do so,” says botanist Ann Sakai. The seeds collected during this study—which may belong to an entirely new species of *Schiedea*—are now growing at the University of California, Irvine, with help from Sakai and her husband, Steve Weller. Both have studied *Schiedea* for more than three decades. “They have been able to map in detail the population in a way that we could just never do by rappelling,” Weller says. —*Susan Cosier*



PLANETARY SCIENCE

Cosmic Cookie Cutter

Astronomers tackle an odd gap in exoplanet sizes

Just 30 years ago scientists weren't sure if any planets existed outside our solar system. Now they've detected more than 5,000 of them. But as astronomers have calculated these exoplanets' sizes, a strange gap has emerged. There are plenty of "super-Earths" out there—rocky orbs about 1.4 times wider than Earth. And there are lots of "mini-Neptunes" roughly 2.4 times Earth's width. But very few planets fall in between; it's almost like most worlds were sized using one of two cookie cutters. A new model published in *Astrophysical Journal Letters* offers a fresh answer to why this is so: it's all about collisions.

Previous hypotheses about the planetary "radius gap" suggested that high temperatures shrink certain planets, says Rice University astrophysicist André Izidoro, lead author of the new study. Planets tend to move closer to their host stars over time, he says. This makes relatively light planets slim down faster as rising heat strips away their outer gases, the thinking goes, whereas heavier planets have enough gravity to hold these gases and maintain their size.

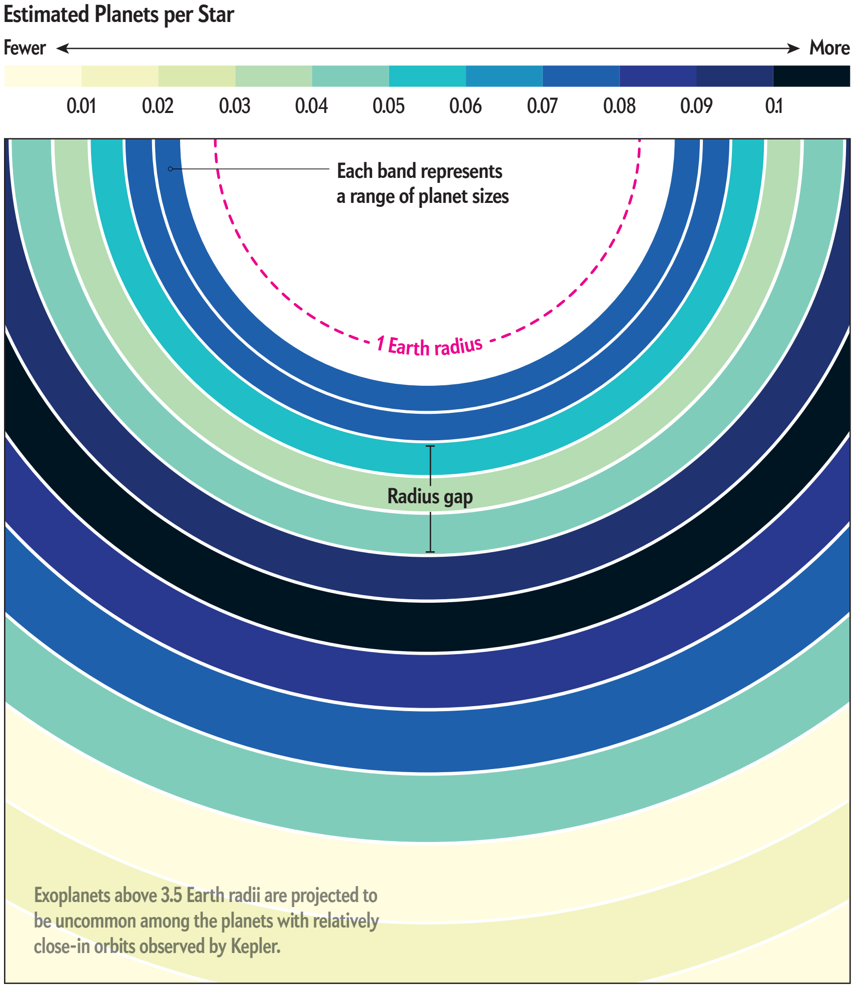
Izidoro's work challenges this heat-based explanation, suggesting the gap results from planetary collisions instead. His team ran computer simulations based on theories of how planetary systems most likely develop: Planets that form close to stars are typically rocky, while farther-flung planets are generally extremely rich in water or ice—and most in both categories start out in the larger, mini-Neptune size range, Izidoro says.

As planetary systems age and young planets drift toward their stars, the planets' orbits become unstable, and they often collide. When rocky planets smash together, they have a greater combined mass, Izidoro says. But they also lose gas layers, so their combined radius tends to decrease; the two form a single, denser planet. When two water-rich planets collide, Izidoro adds, "their size does not change that much because water is less dense, so they still stay above the radius valley" even after outer gases disappear. And a rocky planet colliding with a water-rich planet usually leads to a bigger water-rich planet—again above the radius gap.

For this collision model to hold true, planets must not lose as much mass to heat as had previously been thought, says James Owen, an astrophysicist at Imperial College London who was not involved in the new study. But on the other hand, Owen notes, "if you believe the mass-loss models, then you'd have to suggest that collisions between planetary bodies ... are much less frequent than we think."

To test both hypotheses, Owen says future high-resolution space telescopes could observe the makeup of mini-Neptunes. If exoplanets in this size range contain lots of hydrogen and helium, that would favor the mass-loss picture; a high proportion of water and ice would support the collision explanation.

Yet "there's no way to answer our questions entirely by observational means," says study co-author Hilke Schlichting, an astrophysicist at the University of California, Los Angeles. Planets' formation over millions of years cannot be observed in real time. "I think you need modeling research to understand what the data really tell us," Schlichting says—and such insights "may revolutionize our thinking about the formation of our own solar system." —*Daniel Leonard*



After NASA's Kepler mission identified hundreds of new exoplanets, astronomer Benjamin J. Fulton refined the data and identified two clear peaks in exoplanet sizes, separated by a "radius gap" where planets are much scarcer. These data continue to inform new studies. (Values for planets below 1.2 Earth radii are omitted because of poor data quality.)

Source: "The California-Kepler Survey. VII. Precise Planet Radii Leveraging Gaia DR2 Reveal the Stellar Mass Dependence of the Planet Radius Gap," by Benjamin J. Fulton and Erik A. Petigura, in *Astronomical Journal*, Vol. 156, No. 6; November 2018 (*data*)

Graphic by Amanda Montañez

Mieridduryn visualized

Franz Anthony

PALEONTOLOGY

Cambrian Oddity

An ancient nozzle-nosed animal lingered in seemingly modern seas

More than a century ago paleontologist Charles Doolittle Walcott uncovered a very strange fossil in Canada. The finger-sized animal was utterly alien compared to anything around today: it looked like a lobster tail with five eyes and a nozzlelike trunk at one end. This 508-million-year-old organism, named *Opabinia regalis,* seemed an isolated expression of evolution running riot back in the Cambrian period—before a mass extinction swept such oddities away. But now scientists have discovered that such enigmatic creatures survived for tens of millions of years longer than previously thought.

Only last year Harvard University paleontologist Joanna Wolfe and her colleagues described the second such specimen ever found, called *Utaurora.* This creature, unearthed in Utah, was related to *Opabinia* and lived at a similar time. But the day this find was published, Wolfe saw a photograph taken by fellow researcher Stephen Pates that would fundamentally change these organisms' story. Pates had just found a third *Opabinia*-like creature in Wales—in rocks about 40 million years younger than the first two specimens. This oddball would have lived when more modern-looking animals, such as snails, cephalopods and corals, were on the rise.

"My very first reaction was actually that it couldn't be," Wolfe says. The fossil seemed too poorly preserved to immediately identify. But the discovery of another, higher-quality fossil and analysis showing key characteristics in common with *Opabinia* eventually convinced Wolfe. She, Pates and other researchers recently published the finding in *Nature Communications.*

At first glance the new fossil resembles a smear on gray stone. But up close, it clearly shares telltale traits with *Opabinia.* Wolfe and her colleagues called the animal *Mieridduryn* ("bramble snout" in Welsh) for its spiky proboscis.

Finding such specimens in Wales came as a surprise. "Fossils from the Llandrindod Wells area have been studied for many decades and were thought to contain only shelly fossils like trilobites," says paleontologist Rich Howard of the Natural History Museum in London, who was not involved with the discovery. No one was looking for small, soft-bodied creatures there. Such fossils are invaluable for understanding the origins and early days of groups such as arthropods and their soft-bodied precursors.

Mieridduryn lived during the Ordovician period, as Earth's oceans were starting to resemble something a little more familiar to us today. Various other Cambrian oddities are now known to have lived beyond the mass extinction into that new era—and researchers are still investigating how they did so, as well as why they ultimately vanished. "We have more questions now about how opabiniids may have survived and what kinds of environments or life histories they were restricted to," Wolfe says. And now she has an additional 40 million years' worth of rocks to examine for clues.

—*Riley Black*

NEWS AROUND THE WORLD

Quick Hits

By Daniel Leonard

BAHAMAS
Biologists strapped small cameras onto tiger sharks to study seagrass in the Caribbean. The footage helped expand estimates of the global area of seagrass coverage by 41 percent—a good sign for the climate because seagrass stores carbon.

CHINA
Scientists have struggled to identify the creatures that left behind the world's oldest skeletal remains—500-million-year-old tubelike structures. Now a new analysis of specimens from Yunnan (including a rare look at their fossilized soft tissues) suggests the animals were jellyfish relatives that resembled sea anemones.

MALAYSIA
Researchers have produced stem cells using skin from Malaysia's last male Sumatran rhinoceros, Kertam, who died in 2019. Converting these cells into viable spermatozoa could help to save the critically endangered animal from extinction.

MEXICO
Archaeologists unearthing an administrative complex of the ancient city Teotihuacán found the roughly 1,700-year-old skeleton of a spider monkey that was not native to the region. Experts suspect it was a gift from the neighboring Maya, pointing to previously unknown animal-based diplomacy.

REPUBLIC OF CONGO
A new study suggests the Congo peatlands have alternated—every few thousand years—between releasing carbon dioxide (when dry) and storing it (when wet). This may mean the peatlands are a climate change "time bomb" set to release stored carbon as they dry.

U.K.
A meteorite that landed in an English driveway has been found to contain water with a ratio of hydrogen isotopes resembling Earth's. This supports the idea that the young Earth's water could have been brought by asteroids.

For more details, visit www.ScientificAmerican.com/feb2023/advances

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Burmese python extends its jaw.

Hillary Kladke/Getty Images

BIOLOGY

Open Wide

Snake's dramatic jaw stretch measured for the first time

Invasive Burmese pythons slithering through the Florida Everglades eat almost anything they can get their jaws around—and that's a lot. As the snakes' numbers have risen, small mammal populations have plummeted. But larger animals aren't safe either; people have spotted these pythons swallowing alligators and white-tailed deer whole. How do snakes with mouths a few inches wide devour something that huge?

Answer: They open their mouths very wide, with the help of some newly measured stretching power. A recent study shows Burmese pythons' mouths can stretch four times wider than their skulls, creating a gaping maw four to six times bigger than a similarly sized brown tree snake's.

Most snakes cannot take bites and must engulf prey whole. To do so, a typical snake opens its mouth at the joint in the middle of its jaw, and the two halves of the lower jaw flare out to the sides; the skin and tissue in between stretch to accommodate the food. The skin eventually snaps back, but "after they swallow a very big meal, [their chins] are baggy for a while," says University of Cincinnati vertebrate morphologist Bruce Jayne.

And some snakes can open wider than others. For a study in *Integrative Organismal Biology,* Jayne and his colleagues examined Burmese pythons from Florida and brown tree snakes from Guam (where the latter are invasive). The researchers took anatomical measurements of snakes after death, then stretched the reptiles' jaws with funnels of increasing size. Finally, the scientists stuffed potential prey—including anesthetized alligators—through the funnels and measured deer remains recovered from a python stomach.

The experiment showed just how wide each species' mouth could get. The secret to the Burmese pythons' superior skill? Extra stretch in the tissues between their jaw bones. Some 43 percent of their gap width capacity could be attributed to this tissue, compared with 17 percent for the tree snakes.

According to Marion Segall, a herpetologist at London's Natural History Museum, who was not involved in the study, the two distantly related invasive snakes make a good comparison because they have each evolved to snag large prey relative to their sizes. Future work will explore what properties make the pythons' jaws so flexible.

Just because a python can eat a whole deer doesn't mean venison is often on the menu. "Most [tree snakes and pythons] are opportunistic and will catch anything that passes by, [so] they will probably not target the largest prey," Segall says. But to avoid presenting such an opportunity in the Everglades, even a big deer should probably sleep with one eye open. *—Bethany Brookshire*

ANIMAL BEHAVIOR

Impressive Pick

An aye-aye's freaky finger facilitates the ultimate picked nose

A long-fingered lemur has been caught on camera picking its nose—and eating the slimy goods.

The culprit was Kali, an aye-aye at the Duke Lemur Center who now has the dubious honor of being the first of her species ever recorded nose picking, researchers say. What's more, Kali earned this distinction with an aye-aye's bizarrely long middle finger; when fully inserted in her nose, it reached all the way into her throat. "I was really impressed," says Anne-Claire Fabre, an evolutionary biologist at the University of Bern and the curator of mammals at the Natural History Museum of Bern in Switzerland. She and her colleagues reported the findings in the *Journal of Zoology*.

Fabre was studying lemur grasp when she happened to catch Kali "digging for gold." She and her team subsequently searched in the research literature for other examples of primate nose pickers and found that at least 11 other species besides aye-ayes are guilty of the habit. Others include chimpanzees, gorillas, capuchin monkeys and, yes, humans. Surveys have found nose picking to be extremely common in our species, with almost entire samples of teens and adults admitting to the habit privately.

But the champion nose picker has got to be the aye-aye. These lemurs' middle fingers are more than three inches long and very spindly. Aye-ayes use the weird digits to tap on logs extremely rapidly, reaching at least seven raps per second while listening with their batlike ears for the sound of voids in the wood—tunnels gnawed by insects. Then they mentally map these tunnels, bite holes at intersections and plunge their middle fingers in to pull out grubs, says North Carolina State University biologist Adam Hartstone-Rose, who was not involved in the new research. While fingers in the animal kingdom almost always have hinge joints that bend forward and back, Hartstone-Rose says, the aye-aye's middle finger joint is a ball-and-socket, allowing it to rotate and turn almost like a human shoulder.

Some researchers have speculated that nose picking might offer immune system advantages or some other benefit, although Fabre says no firm science backs that up. But primates, in general, are pickers, Hartstone-Rose says: they pull parasites off one another, pick at scabs, put Q-tips in their ears against medical advice, and generally use their dexterity to groom themselves and others.

"I think the finger evolved to do this amazing 'fishing' behavior" in logs, Hartstone-Rose says, "and just because it has that anatomy and that sensitivity, it basically freed it to be able to do this other disgusting thing." —*Stephanie Pappas*

Marko von der Osten/Alamy Stock Photo

ATMOSPHERIC SCIENCE

Weird Weather

How to tell a williwaw from a haboob

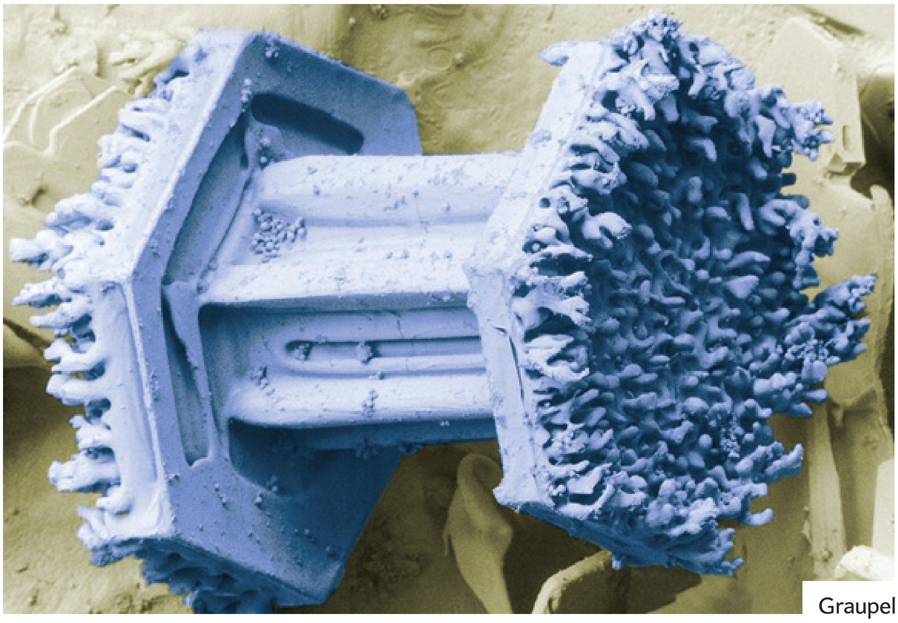
Extreme weather is increasingly in the news. We're accustomed to hearing about unusually strong hurricanes, tornadoes and even the polar vortex, but atmospheric events can get a lot weirder—as can the names we give them. Read on for some of the most bizarre weather phenomena and their intriguing monikers. —*Mark Fischetti*

ATMOSPHERIC RIVER A "river" of water vapor in the sky that can grow to 2,000 miles long, 500 miles wide and two miles deep. Strong winds sometimes push these series of connected rainstorms from mid-ocean areas toward continents' western coasts. The heaviest atmospheric rivers strike the U.S. and Canada—where they can carry vapor equivalent to 25 times the flow of the Mississippi River and can trigger the biggest floods in a century. In 1861 one turned California's Central Valley into an inland sea, 300 miles long and 20 miles wide, for almost a year. Some forecasters call an atmospheric river a pineapple express if it rolls in from the region of Hawaii.

BOMB CYCLONE A rotating, rapidly intensifying storm that brings heavy rain or snow. A bomb cyclone is formed by bombogenesis—when a storm's barometric pressure plummets by at least 24 millibars in 24 hours, causing the system to "blow up" in strength. The nastiest nor'easters (storms that spin up along the U.S. East Coast and typically result in strong winds over the Northeast) are often caused by bombogenesis.

FIRENADO A spinning vortex of hot air, gases and embers that rises rapidly from an intense wildfire and can lift smoke, debris and flames hundreds of feet into the atmosphere. Fire whirls and firenadoes range from

Firenado



Graupel

Haboob

USFS Photo/Alamy Stock Photo (top); Science Source (middle); Jordistock/Getty Images (bottom)

a few feet to 500 feet in diameter, and the largest ones can carry embers long distances.

GRAUPEL Frosty weather can bring soft snowflakes and hard hail pellets. In between, there's graupel—a kind of soft hail. In uncommon atmospheric circumstances, very cold water droplets in the air freeze onto snowflakes and fall with them, hitting the ground with a squishy plop.

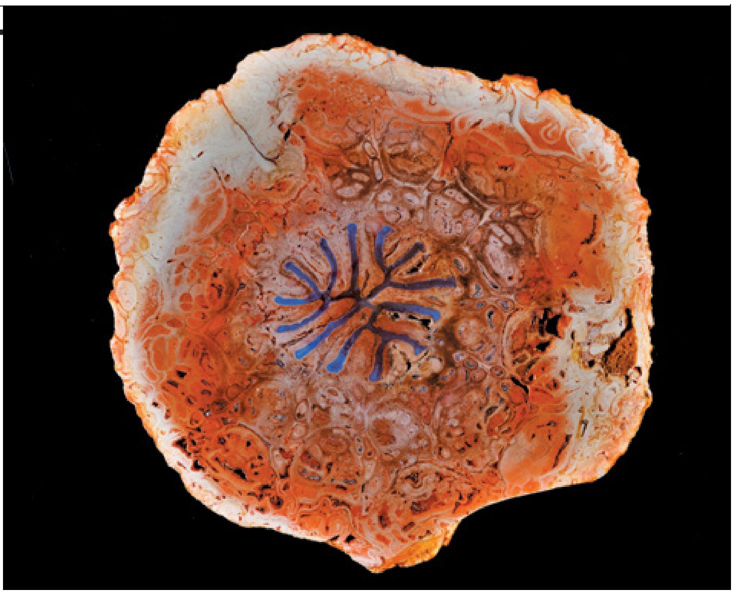
HABOOB This term is derived from Arabic, and it describes a thick, violent dust storm or sandstorm. The word has caught on as more intense haboobs have cut across the Middle East, northern Africa and India, grabbing media coverage. Winds can drive dust at up to 60 miles per hour, crippling transportation and infiltrating people's lungs, even though these events often pass in less than an hour.

POGONIP Fog is typically made of water vapor, but sometimes ice particles also create an ephemeral mist. When the air temperature is below freezing and relative humidity is greater than 100 percent—an infrequent combination—ice crystals can form and hover to form a "pogonip," or ice fog. Pogonips typically happen in deep mountain valleys. The term is usually credited to the Shoshone people of North America: it is said to be derived from the word *payinappih,* which means "cloud."

STORM QUAKE Some storms that rage over the ocean, notably hurricanes, can generate very large waves that crash downward into the seafloor. This process occasionally sets off vibrations in Earth's surface similar to those from an earthquake. Researchers discovered this phenomenon only a few years ago, but by studying seismic records and past storm tracks, they found that thousands of storm quakes had occurred from 2006 to 2019 near the U.S. and Canadian coasts. Some were as strong as magnitude 3.5 earthquakes.

DOWNBURST Severe thunderstorms can spin up tornadoes, but they can also produce powerful winds that have no rotation. The latter are called straight-line wind. In these cases, the storm draws high-altitude air straight downward. When it hits the ground, this "downburst" fans out in a straight line, with wind that can exceed 100 mph, causing dangerous conditions and property damage. A "microburst" is a highly localized downburst.

WILLIWAW A sudden, fierce gust of cold, dense air that dives down from mountaintops along a coast. This downward blast can roil coastal waters, wreaking havoc on ships. Williwaws occur most often at very high latitudes, such as the Aleutian Islands off Alaska and the Strait of Magellan at Chile's southern tip. Gore Vidal wrote his first novel, *Williwaw,* while stationed on a U.S. Army supply ship in the Aleutian Islands in the 1940s.



Fossilized stem cross section with water-conducting tissues highlighted in blue

Ludwig Luthardt/Museum für Naturkunde, Berlin (CC-BY license)

EVOLUTION

Green Plumbing

Plants evolved complex water transport systems to survive on land

Towering redwoods and lanky jungle vines hoist water from the soil to their lofty leaves through a tubelike tissue called the xylem. In early plants, which reached just a few centimeters and lived only in wet environments, the xylem worked like a simple cylindrical bundle of drinking straws running up the stem; our modern biosphere exists because that infrastructure somehow got much more sophisticated.

The ecosystems "that have been the backdrop for the evolution of life on land weren't actually there until vascular plants figured out how to grow big in a relatively dry place," says Czech Academy of Sciences biologist Martin Bouda.

Many modern xylems have intricate cross sections that look like gappy rings, crosses, diamonds or hearts, with dead space called pith separating bundles of xylem tissue. But what nudged plants to remodel their pipes this way is a century-old mystery. Bouda and his colleagues proposed recently in *Science* that plants developed complex xylems to withstand drought.

Water lost from leaves to dry air cannot be easily replaced from parched soil. Trying to do so strains the xylem, introducing air bubbles that clog the tubes and starve tissues of water—similar to the way that deadly air embolisms cut off animals' blood flow. Bouda's team used simulations based on modern and fossil plants to show how modern xylems' gaps and dead ends hinder such bubbles from spreading.

But smaller-scale tweaks to xylem cells and tissue organization can protect against drought, too, says Cornell University evolutionary biologist Jacob Suissa, who was not involved in the new study. Complex cross sections might have simply arisen incidentally as plants got bigger. "On an evolutionary timescale, size is correlated with increasing complexity," he says, adding that it's important to "question the line of thinking that every trait has to be adaptative."

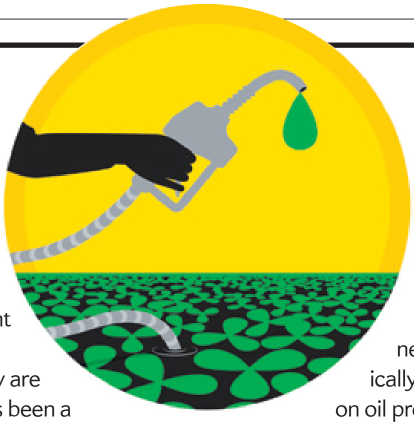
Suissa suggests that carefully comparing the xylems of plants from different climates could resolve some of the remaining ambiguity.

Nevertheless, the new study highlights the potentially enormous consequences of tiny evolutionary adjustments. Without drought-resistant plant pipes, Bouda says, "it's hard to imagine what the planet and the species living on it would look like." *—Elise Cutts*

ENERGY

Duckweed Power

Common water plant could provide a green energy source



Scientists have figured out how to coax copious amounts of oil from duckweed, one of nature's fastest-growing aquatic plants. Converting such plant oil into biodiesel for transportation and heating could be a big part of a more sustainable future.

For a new study in the *Plant Biotechnology Journal,* researchers genetically engineered duckweed plants to produce seven times more oil per acre than soybeans—currently the most commonly used biodiesel-producing plant. Study lead author John Shanklin, a biochemist at the U.S. Department of Energy's Brookhaven National Laboratory, says further research could double the engineered duckweed's oil output in the next few years. Shanklin and his colleagues conducted the study with researchers at New York's Cold Spring Harbor Laboratory.

Unlike fossil fuels, which form underground over hundreds of millions of years, biofuels can be replenished faster than they are used. Fuels made from new and used vegetable oils, animal fat and algae can have a lower carbon footprint than fossil fuels do, depending on how they are sourced—but there has been a recent backlash against them. This is partly because so many crops now go into energy production rather than food; biofuels take up more than 100 million acres of the world's agricultural land.

Duckweed, common on every continent but Antarctica, is among the world's most productive plants per acre, and the researchers suggest it could be a game-changing renewable energy source for three key reasons. First, it grows readily in water, so it wouldn't compete with food crops for prime agricultural land. Second, duckweed can thrive in agricultural pollution from, say, pig and poultry farms—potentially cleaning up some of the nitrogen and phosphorus such farms release into the water.

Third, Shanklin and his team found a way to sidestep a major biotechnological hurdle: According to Rebecca Roston, a biochemist at the University of Nebraska–Lincoln, who was not involved in the study, engineered green plants typically expend a lot of energy on oil production and thus stop growing. For the new study, Shanklin says, the researchers added an oil-producing gene that would be inactive at first, "turning it on like a light switch" by introducing a particular molecule only when the plant had finished growing.

This process "worked fabulously well," Roston says. "If it replicates in other species—and there's no reason to think that it would not—this can solve one of our biggest issues, which is how can we make more oil in more plants without negatively affecting growth."

To scale production up to industrial levels, scientists will need to design and produce large-scale vessels for growing engineered plants and extracting oil—a challenge, Shanklin says, because duckweed is a nonmainstream crop without much existing infrastructure. —*Cari Shane*

ANTHROPOLOGY

Major Miners

Ancient pollution reveals large-scale mining in prehistoric North America

Copper's allure has endured for millennia. Both ancient and modern mines for the extremely useful metal abound in North America's Lake Superior region; long before modern miners extracted the ore from deep underground, local Indigenous communities dug it from shallow pit mines.

These prehistoric mines' ages were a "long-standing mystery," says David Pompeani, a geologist at the University of Hawaii at Mānoa. Previous research used archaeological remnants to evaluate when mine sites were active, but later mining at the same sites often obliterated ancient artifacts, Pompeani says. To work around this, he and his colleagues took a different approach: instead of artifacts, they looked for signs of mining preserved in the environment.

For a recent study in *Anthropocene,* the researchers examined sediments from two small inland lakes near ancient mines on Lake Superior's isolated Isle Royale in Michigan. Such sediments are affected by annual changes and thus act a little like tree rings. Each layer is a snapshot of what happened in a given year, including weather events, wildfires—and pollution.

Even preindustrial copper mining produced pollution, mainly from lead impurities in copper deposits. "Lead is a good proxy to record human impact … it's not a metal we can get in a natural way," says Francisca Martínez-Ruiz, a geochemist at Instituto Andaluz de Ciencias de la Tierra in Spain, who was not involved in the study.

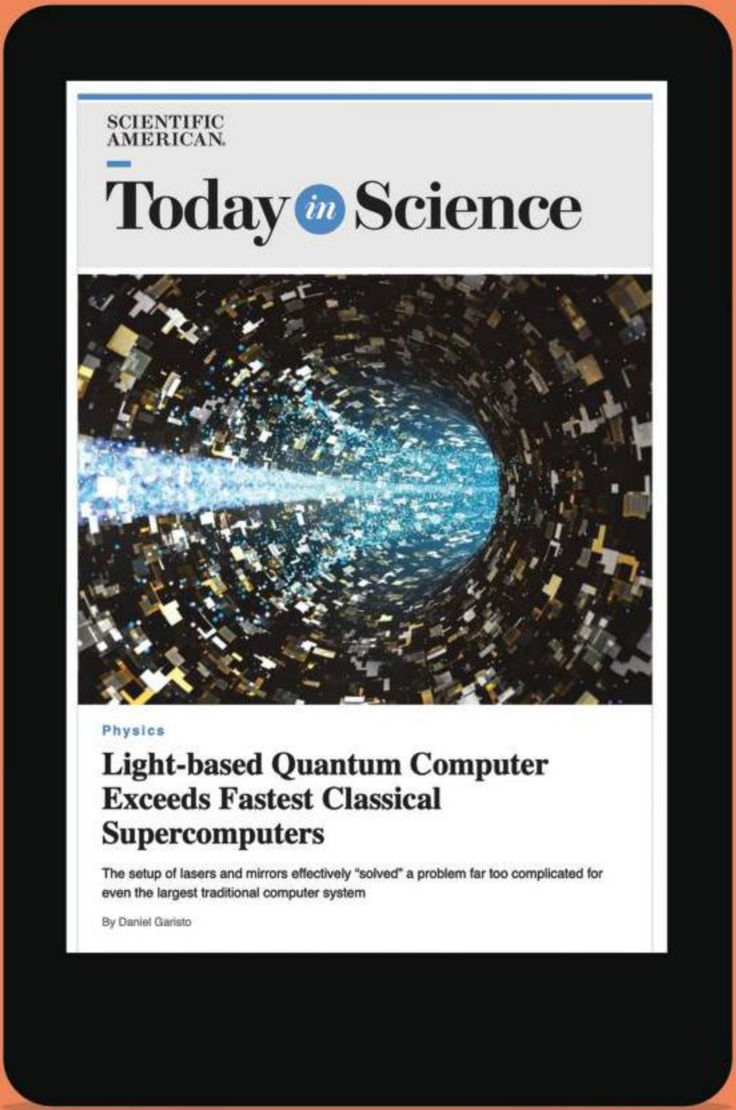
Before modern machinery, extracting copper was labor-intensive. Native Americans hammered it out of the rock—hard, dusty work that lofted fine particles of stone and metals into the air. Pompeani says they probably also used bonfires to warm this rock, softening the copper and liquefying the easily meltable lead. These fires volatilized the lead and wafted it over the surrounding area, sprinkling particles onto the land and lakes. Analyzing lake sediments, the researchers found evidence of a peak in lead pollution around 6,000 years ago during the Archaic period. This suggested a simultaneous peak in large-scale copper mining—and matched archaeological evidence from the same period.

"The paper shows that the lead is a reliable proxy that can be used for reconstruction in this region," Martínez-Ruiz says. She adds that similar studies of small lakes' environmental pollution could be used to investigate human impacts worldwide.

Pompeani says the study confirms some of the world's earliest-known large-scale mining efforts and puts a new spin on how Indigenous societies operated. "There's this idea that hunter-gatherers couldn't organize to conduct a mining operation," he says. "Yet that lake sediment indicates that during the Archaic period, they mined to such a degree that we can detect it in the environment."

—*Sarah Derouin*

Illustration by Thomas Fuchs



METER

Edited by Dava Sobel

Lorraine Schein, a New York writer, has contributed to VICE *Terraform, Strange Horizons, Poetry New York,* and the anthology *Tragedy Queens: Stories Inspired by Lana Del Rey & Sylvia Plath.* Her new book, *The Lady Anarchist Café,* is out now from Autonomedia.

A Quantum Cento

Time crystals could soon escape the laboratory.
These quantum systems made of time and light
are potential fugitives into our reality.

By shining twin laser beams piped
into a tiny disk-shaped crystal cavity
this new class of matter was created unexpectedly.

Detected by emitted luminosity,
they spin and oscillate to the same height
repeating to the same frequency—
like ticking clocks with a predictable periodicity,
but patterned across time, invisible to sight.

These structures from quantum impracticality,
inherent crystalline metronomes might
migrate into our future time-keeping technology.

Author's Note: A cento, from the Latin for "patchwork," is a collage poem composed of lines from other sources. This poem borrows phrases from a *Scientific American* article entitled "Time Crystals Made of Light Could Soon Escape the Lab," by Karmela Padavic-Callaghan.

Illustration by Mark Ross

Claudia Wallis is an award-winning science journalist whose work has appeared in the *New York Times, Time, Fortune* and the *New Republic.* She was science editor at *Time* and managing editor of *Scientific American Mind.*

Beyond the Golden Rule

Clinicians need to understand patients' values, not apply their own

By Claudia Wallis

For much of human history and across multiple cultures, ethical behavior has been guided by the Golden Rule: do unto others as you would have them do unto you. When we act with empathy and compassion, we draw on this cherished principle. But the rule is imperfect. People vary greatly in their values, lived experiences and sense of what is acceptable. What you would want in a given situation may not be what another person desires at all.

In the arena of medicine, the stakes for making or influencing choices for others can be especially high. Such choices impact people's quality of life and even their chances of survival. As health care becomes less paternalistic and more individualized, the time seems right for a new ethical guideline. Enter the "platinum rule," proposed by Harvey Max Chochinov, a professor of psychiatry at Canada's University of Manitoba: do unto others as they would want done unto themselves.

Chochinov, an expert on palliative care, eloquently describes this principle in his essay "Seeing Ellen and the Platinum Rule," published last year in *JAMA Neurology.* He begins with a story about a health crisis affecting his late sister Ellen, who was severely disabled by cerebral palsy. The intensive care doctor managing her case, after seeing her twisted body and respiratory distress, was weighing whether to insert a breathing tube when he asked Chochinov a peculiar question: Did Ellen read magazines? "The subtext was chilling," Chochinov writes, because "this was not an attempt to get to know Ellen … but rather a cryptic way of deciding if hers was a life worth saving." Ellen, her brother knew, read widely and relished many simple pleasures of life, but the gulf between her life as a frail person who uses a wheelchair and the physician's sense of what he would want in her situation was too vast to be bridged by the Golden Rule.

"When the lived experience of another, the sensibility and perspective of another, varies widely from your own perspective, that's when using yourself as this infallible barometer of what another might need or want begins to break down," Chochinov explained to me. "We have to acknowledge the ways in which our own personal biases can shape the way we perceive and respond to patients."

Those patients can differ from health-care workers by more than their abilities or disabilities. Their values can also be shaped by race, culture and experience. In a diverse society, doctors ought not project their values and presumptions onto the patient "as if the patient were a blank screen or clone of the doctors themselves," observes Catherine Frazee, a disability advocate, author and emerita professor of disability studies at Toronto Metropolitan University. Medical practitioners, she adds, "are well educated, well respected and well paid. Those three things alter the way you see the world. So there is a real bias."

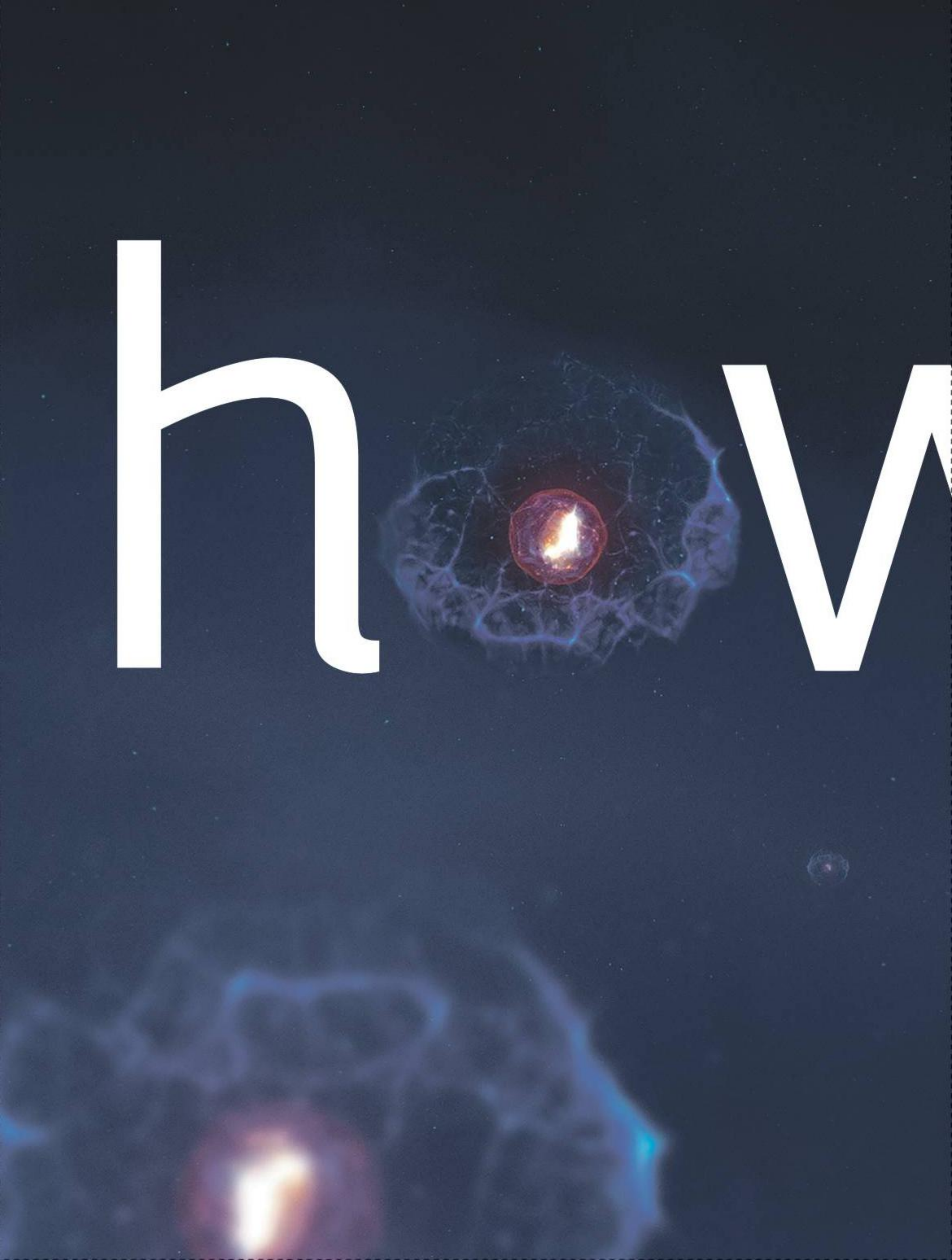
The platinum rule is not entirely new. But in medicine, it pulls together current ideas about patient autonomy, equity and diversity in a succinct formulation that "is quite brilliant" and well suited to being taught to health practitioners, says medical ethicist Joseph Fins of Weill Cornell Medicine. Indeed, within weeks of writing about the idea in *JAMA Neurology* and in the *Journal of Palliative Medicine,* Chochinov began to hear of its uptake at a medical ethics conference and, before long, in other journal articles.

Making the effort to understand a patient's personal needs and wishes does not mean catering to all of them. Medicine can't be "a take-out service," Chochinov says. "Not all patients can receive all things at all times. That's the reality of living with a health-care system that has limited resources." One of those limited resources is time, and there's no denying that getting to know a patient as an individual—as opposed to the generic host of a disease—means investing additional minutes or hours. Still, Fins believes that such investment is usually cost-effective: "If we know what patients want, we will spend less time giving them things they don't want."

There are benefits for the clinician as well. "When doctors emotionally connect to their patients, they do a better job," Chochinov says. "And we have data to show there is heightened job satisfaction and less burnout."

In cases where patients cannot speak for themselves and where loved ones are uncertain of their wishes, clinicians may find it hard to apply the platinum rule. But, as Frazee sees it, there is value in the effort: "At the very least, your attempt to work through it will ensure that you have sufficient humility about the wisdom of your choices."

Illustration by Jay Bendt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The AI Biologist

DeepMind's Demis Hassabis explains how artificial intelligence solved one of the biggest problems in biology

By Tanya Lewis

There's an age-old adage in biology: structure determines function. To understand the function of the myriad proteins that perform vital jobs in a healthy body—or malfunction in a diseased one—scientists have to first determine these proteins' molecular structure. But this is no easy feat: protein molecules consist of long, twisty chains of up to thousands of amino acids, chemical compounds that can interact with one another in many ways to take on an enormous number of possible three-dimensional shapes. Figuring out a single protein's structure, or solving the "protein-folding problem," can take years of finicky experiments.

But last year an artificial-intelligence program called AlphaFold, developed by the Alphabet-owned company DeepMind, predicted the 3-D structures of almost every known protein—about 200 million in all. DeepMind CEO Demis Hassabis and senior staff research scientist John Jumper were jointly awarded one of this year's $3-million Breakthrough Prizes in Life Sciences for the achievement, which opens the door for applications that range from expanding our understanding of basic molecular biology to accelerating drug development.

DeepMind developed AlphaFold soon after its AlphaGo AI made headlines in 2016 by beating world Go champion Lee Sedol at the game. But the goal was always to develop AI that could tackle important problems in science, Hassabis says. DeepMind has made the structures of proteins from nearly every species for which amino acid sequences exist freely available in a public database.

Scientific American spoke with Hassabis about developing AlphaFold, some of its most exciting potential applications and the ethical considerations of highly sophisticated AI. [*An edited transcript of the interview follows.*]

Illustration by Joe Anderson

Tanya Lewis is a senior editor covering health and medicine for *Scientific American.*

Why did you decide to create AlphaFold, and how did you get to the point where it can now fold practically every known protein?

We pretty much started the project roughly the day after we came back from the AlphaGo match in Seoul, where we beat Lee Sedol, the world [Go] champion. I was talking to Dave Silver, the project lead on AlphaGo, and we were discussing "What's the next big project that DeepMind should do?" I was feeling like it was time to tackle something really hard in science because we had just solved more or less the pinnacle of games AI. I wanted to finally apply the AI to real-world domains. That's always been the mission of DeepMind: to develop general-purpose algorithms that could be applied across many, many problems. We started off with games because it was more efficient to develop AI and test things out in games for various reasons. But ultimately that was never the end goal. The end goal was to develop things like AlphaFold.

It's been a mammoth project—about five or six years' worth of work before CASP14 [the 14th Critical Assessment of Structure Prediction, a protein-folding competition]. We had an earlier version at the CASP13 competition, and that was AlphaFold 1. That was state of the art, you know, a good deal better than anyone had done before and I think one of the first times that machine learning had been used as the core component of a system to try to crack this problem. That gave us the confidence to push it even further. We had to reengineer things for AlphaFold 2 and put a whole bunch of new ideas in there and also bring onto the team some more specialists—biologists and chemists and biophysicists who worked in protein folding—and combine them with our engineering and machine-learning team.

I've been working on and thinking about general AI for my entire career, even back at university. I tend to note down scientific problems I think one day could be amenable to the types of algorithms we build, and protein folding was right up there for me always, since the 1990s. I've had many, many biologist friends who used to go on about this to me all the time.

Were you surprised that AlphaFold was so successful?

Yeah, it was surprising, actually. It's definitely been the hardest thing we've done, and I would also say the most complex system we've ever built. The *Nature* paper that describes all the methods, with the supplementary information and technical details, is 60 pages long. There are 32 different component algorithms, and each of them is needed. It's a pretty complicated architecture, and it needed a lot of innovation. That's why it took so long. It was important to have all these different inputs from different backgrounds and disciplines. And I think something we do uniquely well at DeepMind is mix that together—not just machine learning and engineering.

But there was a difficult period after AlphaFold 1. We first tried to push AlphaFold 1 to the maximum. And we realized about six months after CASP13 that it was not going to reach the atomic accuracy we wanted to actually solve the problem and be useful to experimentalists and biologists. So I made the decision that we needed to go back to the drawing board and take the knowledge we had acquired, including where it worked and where it didn't work, and then see if we could go back to almost a brainstorming stage with that experience and that knowledge and come up with a whole bunch of new ideas and new architectures. We did that, and ultimately that worked.

But for about six months to a year after that reset, things got worse, not better. The AlphaFold 2 system, the early one, was much worse than AlphaFold 1. It can be very scary during the period where you seem to be going backward in terms of accuracy. Fortunately, that's where our experience in games and all the other AI systems we built before came into play. I'd seen us go through that valley of death and then get out the other side.

Can you explain, on a very simple level, how AlphaFold works?

It's a pretty complicated thing. And we don't know a lot of things for sure. It's clear that AlphaFold 2 is learning something implicit about the structure of chemistry and physics. It sort of knows what things might be plausible. It's learned that through seeing real protein structures, the ones that we know of. But one of the innovations we had was to do something called self-distillation, which is to get an early version of AlphaFold 2 to predict lots of structures—and to predict the confidence level in those predictions.

One of the things we built in was this understanding of chemical bond angles, as well as evolutionary history, using a process called multisequence alignment. These bring in some constraints, which help to narrow the search space of possible protein structures. The search space is too huge to solve it by brute force. But obviously real-world physics solves this somehow because proteins fold up in nanoseconds or milliseconds. Effectively, we're trying to reverse engineer that process by learning from the output examples. I think AlphaFold has captured something quite deep about the physics and the chemistry of molecules.

The fascinating thing about AI in general is that it's kind of a black box. But ultimately it seems like it's learning actual rules about the natural world.

Yeah, it's almost learning about it in an intuitive sense. I think we'll have more and more researchers looking at protein areas that AlphaFold is not good at predicting and asking, "Are they actually disordered in biology when the protein doesn't have a clear shape, when it's not interacting with something?" About 30 percent of proteins [from organisms with a nucleus] are thought to be disordered. A lot of those kinds of proteins are implicated in disease, such as neurodegeneration, because they might get tangled. And you can see how they might do so because they're just sort of floppy strings rather than forming structures.

The other extremely important thing we did with AlphaFold 2, which we don't do with machine-learning systems, was output a confidence measure on every single amino acid because we wanted a biologist to be able to know which parts of the prediction they could rely on without needing to understand anything about the machine learning.

What are some of AlphaFold's most exciting applications?

We have a lot of nice case studies from partners—early adopters—that have had a year to work with AlphaFold. They're doing an incredibly diverse set of things, from addressing antibiotic resistance to tackling plastic pollution by designing plastic-eating enzymes. I've been talking to [CRISPR gene-editing pioneer] Jennifer Doudna about alfalfa crop sustainability—her team is trying to engineer crops to be a bit more sustainable in the face of climate change.

There's also lots of very cool fundamental research being done with it. There was an entire special issue of *Science* on how scientists solved the structure of the nuclear pore complex. This group of membrane-spanning proteins in the nucleus of eukaryotic cells is one of the biggest proteins in the body. Several groups solved it at the same time from the cryo-EM [cryogenic electron microscopy] data—but they all needed AlphaFold predictions to augment those data in some places. So a combination of experimental structural data with AlphaFold turns out to be a boon to structural biologists, which we weren't necessarily predicting.

> **"We started off with games because it was more efficient to develop AI and test things out in games for various reasons. But ultimately that was never the end goal. The end goal was to develop things like AlphaFold."** —*Demis Hassabis*

And then in practical terms, almost every pharma company we've talked to is using AlphaFold. We'll probably never know what the full impacts are because obviously they keep that proprietary. But I like to think we've helped accelerate drug development and cures for diseases by a few years.

There's been a lot of hype around AI and everything it can do, especially for science and medicine. But AlphaFold seems to have a clear benefit.

I mean, it's for you to decide. But I would say I've had a lot of people tell me that it's the most concrete, useful case of AI doing something in science. I like the fact that we're delivering on the promise of AI. I mean, you could say "hype," but we try and let our work speak for itself.

I remember when we started in 2010, nobody was working on AI. And 12 years later it seems like everyone and their dog are talking about it. And in most cases, as I'm sure you have to sift through all the time, it's like they don't know what AI even is sometimes, or they're misusing the term, or it's not that impressive what's going on. But I think AlphaFold is a very good proof of concept or role model of what could happen. And I think we're going to see much more of that in the next decade—of AI helping to genuinely accelerate some scientific breakthroughs—and we hope to be part of a lot more. We think it's just the beginning.

AI has been in the news a lot lately, whether for producing intelligent language or creating digital art. As AI becomes a bigger part of our lives, how should we think about its consequences?

We at DeepMind have our own internal versions of large language models and text-to-image systems, and we'll probably be releasing some of them at some point [in 2023]. It's really interesting seeing the explosion of developments. AlphaFold, obviously, is huge in the scientific community. But with language and image AIs, it's starting to break through into the mainstream. Everyone, of course, knows about language and can appreciate images—you don't have to have any scientific expertise.

But I think we should always be thinking about the ethical issues, and that's one reason we haven't released our language-based AI yet. We're trying to be responsible about really checking what these models can do—how they can go off the rails, what happens if they're toxic, all of these things that are currently top of mind. It's our view that some of these systems are not ready to release to the general public, at least not unrestricted. But at some point, that's going to happen. We have this phrase at DeepMind of "pioneering responsibly." And for me, that's about applying the scientific method to analyzing and building these systems. I think often, especially in Silicon Valley, there's this sort of hacker mentality that "we'll just hack it and put it out there and then see what happens." I think that's exactly the wrong approach for technologies as impactful and potentially powerful as AI.

I've worked on AI my entire life because I think it's going to be the most beneficial thing ever for humanity, for things like curing diseases, helping with climate change, all of this stuff. But it's a dual-use technology: it depends on how, as a society, we decide to deploy it—and what we use it for.

And I think we're seeing the consequences of that with social media.

How is AI being used—or misused—in social media?

It's not proper AI; it's more statistical algorithms. But we've seen the unintended consequences for democracies. Probably the people who created the social media platforms did not have bad intent when they started; it just kind of got out of hand. But we want to make sure that we think about those knock-on effects early, before going, "Oh, oops, this happened," and then trying to bolt the barn door after the horses have left. We shouldn't do that with powerful technologies. We can take some inspiration and advice from, for example, CRISPR and other technologies. I think there are things we can learn from other scientific communities that have tackled these questions.

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ASTROBIOLOGY

Life AS WE DON’T KNOW IT

Scientists are abandoning conventional thinking to search for extraterrestrial creatures that bear little resemblance to Earthlings

By Sarah Scoles

Illustration by William Hand

LIFE ON OTHER PLANETS might not look like any beings we’re used to on Earth. It may even be unrecognizable at first to scientists searching for it.

Sarah Scoles is a Colorado-based science journalist, a contributing writer at *WIRED Science,* a contributing editor at *Popular Science,* and author of the books *Making Contact: Jill Tarter and the Search for Extraterrestrial Intelligence* (Pegasus Books, 2017) and *They Are Already Here: UFO Culture and Why We See Saucers* (Pegasus Books, 2020).

SARAH STEWART JOHNSON WAS A COLLEGE SOPHOMORE WHEN SHE FIRST STOOD ATOP HAWAII'S Mauna Kea volcano. Its dried lava surface was so different from the eroded, tree-draped mountains of her home state of Kentucky. Johnson wandered away from the other young researchers she was with and toward a distant ridge of the 13,800-foot summit. Looking down, she turned over a rock with the toe of her boot. To her surprise, a tiny fern lived underneath it, having sprouted from ash and cinder cones. "It felt like it stood for all of us, huddled under that rock, existing against the odds," Johnson says.

Her true epiphany, though, wasn't about the hardiness of life on Earth or the hardships of being human: It was about aliens. Even if a landscape seemed strange and harsh from a human perspective, other kinds of life might find it quite comfortable. The thought opened up the cosmic real estate, and the variety of life, she imagined might be beyond Earth's atmosphere. "It was on that trip that the idea of looking for life in the universe began to make sense to me," Johnson says.

Later, Johnson became a professional at looking. As an astronomy postdoc at Harvard University in the late 2000s and early 2010s she investigated how astronomers might use genetic sequencing—detecting and identifying DNA and RNA—to find evidence of aliens. Johnson found the work exciting (the future alien genome project!), but it also made her wonder: What if extraterrestrial life didn't have DNA or RNA or other nucleic acids? What if their cells got instructions in some other biochemical way?

As an outlet for heretical thoughts like this, Johnson started writing in a style too lyrical and philosophical for scientific journals. Her typed musings would later turn into the 2020 popular science book *The Sirens of Mars.* Inside its pages, she probed the idea that other planets were truly other, and so their inhabitants might be very different, at a fundamental and chemical level, from anything on this world. "Even places that seem familiar—like Mars, a place that we think we know intimately—can completely throw us for a loop," she says. "What if that's the case for life?"

If Johnson's musings are correct, the current focus of the hunt for aliens—searching for life as we know it—might not work for finding biology in the beyond. "There's this old maxim that if you lose your keys at night, the first place you look is under the lamppost," says Johnson, who is now an associate professor at Georgetown University. If you want to find life, look first at the only way you know life can exist: in places kind of like Earth, with chemistry kind of like Earthlings'.

Much of astrobiology research involves searching for chemical "biosignatures"—molecules or combinations of molecules that could indicate the presence of life. But because scientists can't reliably say that ET life should look, chemically, like Earth life, seeking those signatures could mean we miss beings that might be staring us in the face. "How do we move beyond that?" Johnson asks. "How do we contend with the truly alien?" Scientific methods, she thought, should be more open to varieties of life based on varied biochemistry: life as we don't know it. Or, in a new term coined here, "LAWDKI."

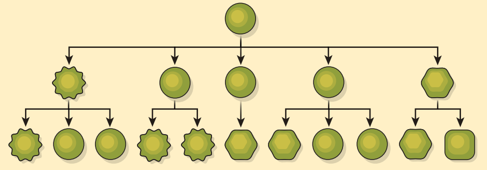
Now Johnson is getting a chance to figure out how, exactly, to contend with that unknown kind of life, as the principal investigator of a new NASA-funded initiative called the Laboratory for Agnostic Biosignatures (LAB). LAB's research doesn't count on ET having specific biochemistry at all, so it doesn't look for specific biosignatures. LAB aims to find more fundamental markers of biology, such as evidence of complexity—intricately arranged molecules that are unlikely to assemble themselves without some kind of biological forcing—and disequilibrium, such as unexpected concentrations of molecules on other planets or moons. These are proxies for life as no one knows it.

Maybe someday, if LAB has its way, they will become more than proxies. These signals could help answer one of humankind's oldest questions—Are we alone?—and show us that we're not so special, and neither is our makeup.

LIFE, ASTRO LIFE OR LYFE

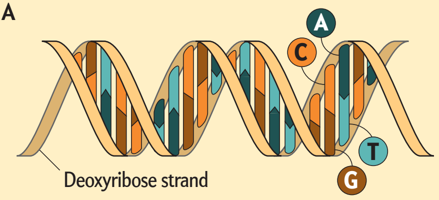
PART OF THE DIFFICULTY in searching for life of any sort is that scientists don't agree on how life started in the first place—or what life even *is*. One good attempt at a definition came in 2011 from geneticist Edward Trifonov, who collated more than 100 interpretations of the word "life" and distilled them into one overarching idea: it's "self-reproduction with variations." NASA formulated a similar working definition years earlier, in the mid-1990s, and still uses it to design astrobiology studies. Life, according to this formulation, "is a self-sustaining chemical system capable of Darwinian evolution."

Life: Self-reproduces with variations



Neither of those classical definitions requires a particular chemistry. On Earth, of course, life runs on DNA: deoxyribonucleic acid. DNA is made up of two twisted strands, each comprising alternating sugar and phosphate groups. Stuck to every sugar is a base—the As (adenine), Gs (guanine), Cs (cytosine), and Ts (thymine). Together the bases and sugar-phosphates form nucleotides; DNA itself is a nucleic acid. RNA is kind of like single-stranded DNA—among other things, it helps translate DNA's instructions into actual protein production.

DNA

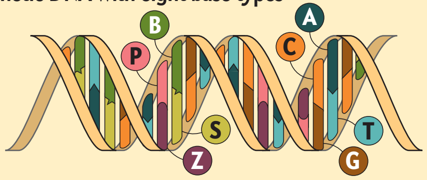


The simple letters in a genetic sequence, strung together in a laddered order, carry all the information needed to make you, squirrels and sea anemones. DNA can replicate, and DNA from different organisms (when they really, really love one another) can mix and meld to form a new organism that can replicate itself in turn. If biology elsewhere relied on this same chemistry, it would be life as we know it.

Scientists assume all forms of life would need some way to pass down biological instructions whose shifts could also help the species evolve over time. But it's conceivable that aliens might not make these instructions out of the same chemicals as ours—or in the same shape. For instance, starting in the 1990s, Northwestern University researchers made SNAs, spherical nucleic acids.

Alien life could have genetic code with, say, different bases. NASA-supported 2019 research, from the Foundation for Applied Molecular Evolution, successfully created synthetic DNA that used the four old-school bases and four new ones: P, Z, B and S. Scientists have also altered the strand part of genetic code, creating XNA—where X means anything goes—that uses a molecule such as cyclohexene (CeNA) or glycol (GNA), rather than deoxyribose. Big thinkers have long suggested that rather than using carbon as a base, as all these molecules do, perhaps alien life might use the functionally similar element silicon—meaning it wouldn't have nucleic acids at all but other molecules that perhaps play the same role. If we can whip up such diversity in our minds and our labs, shouldn't the universe be even more creative and capable?

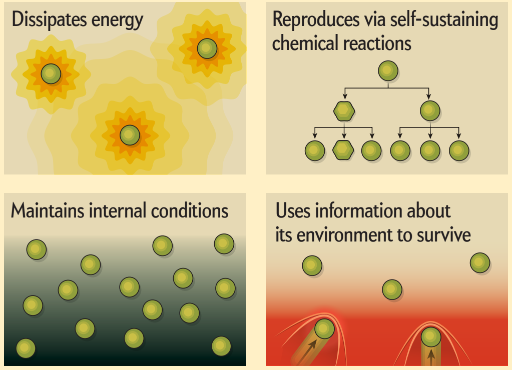
Synthetic DNA with eight base types



It's for that reason that LAB collaborator Leroy Cronin of the University of Glasgow doesn't think scientists should even be talking about *biology* off-Earth at all. "Biology is unique," he proclaims. RNA, DNA, proteins, typical amino acids? "Only going to be found on Earth." He thinks someday people will instead say, "We're looking for "astro life." (LAWDKI has yet to catch on.)

Stuart Bartlett, a researcher at the California Institute of Technology and unaffiliated with LAB, agrees with the linguistic critique. The search for weird life isn't actually a search for life, Bartlett argues. It's a search for "lyfe," a term proposed in a 2020 article he co-authored in, ironically, the journal *Life*. "Lyfe," the paper says, "is defined as any system that fulfills all four processes of the living state." That means that it dissipates energy (by, say, eating and digesting), uses self-sustaining chemical reactions to make exponentially more of itself, maintains its internal conditions as external conditions change, and takes in information about the environment that it then uses to survive. "Life," meanwhile, the paper continues, "is defined as the instance of lyfe that we are familiar with on Earth."

Lyfe: Fulfills all four processes of the living state

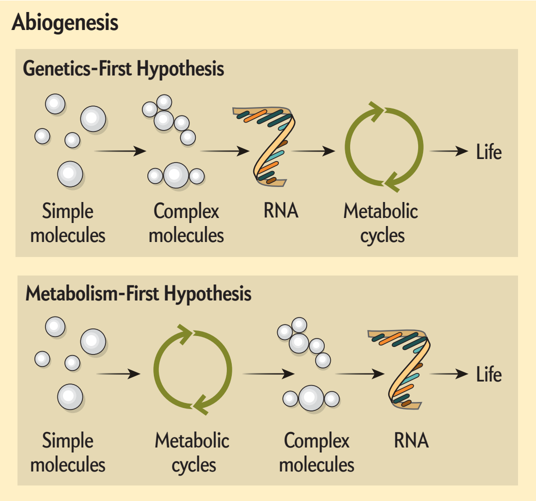


Bartlett's work, though separate from LAB's, emerges from the same fascination: "That mysterious, opaque transition between things like physics and chemistry

Graphics by Jen Christiansen

that we understand fairly well," he says, "and then biology that is still shrouded in mystery." How life becomes life at all is perhaps the most central question of astrobiology.

Trying to figure out how biology emerged on the planet we know best is the province of "origin of life" studies. There are two main hypotheses for how clumps of chemistry became lumps of biology—a process called abiogenesis. One holds that RNA arose able to make more of itself, because that's what it does, and that it could also catalyze other chemical reactions. Over time that replication led to beings whose makeup relied on that genetic code. The "metabolism-first" framework, on the other hand, posits that chemical reactions organized in a self-sustaining way. Those compound communities and their chemical reactions grew more complex and eventually spit out genetic code.


Abiogenesis

Genetics-First Hypothesis

Metabolism-First Hypothesis

Those two main hypotheses aren't mutually exclusive. John Sutherland, a chemist at the Medical Research Council Laboratory of Molecular Biology, is codirector of a group called the Simons Collaboration on the Origins of Life, which merges previous ideas about how one or another subsystem, such as genetics or early metabolism, came first. But if he's being real, Sutherland admits he doesn't understand how biology got started. No one does.

And until scientists know more about how things probably went down on the early Earth, Sutherland argues, there's no way to estimate how common extraterrestrial anything might be. It doesn't matter that there are trillions of stars in billions of galaxies: If the events that led to life are supremely uncommon, those many solar systems might still not be enough, statistically, to have resulted in abiogenesis—in other beings.

BIO-AGNOSTIC

THE FIRST ISSUE of the academic journal *Astrobiology,* more than two decades ago, featured an article by Kenneth Nealson and Pamela Conrad called "A Non-Earth-centric Approach to Life Detection." But taking a non-Earth-centric approach isn't easy for our brains, which formed in this environment. We are notoriously bad at picturing the unfamiliar. "It's one of the biggest challenges we have, like imagining a color we've never seen," Johnson says.

So astrobiologists often end up looking for aliens that resemble Earth life. Astronomers like to consider oxygen in an exoplanet atmosphere as a potential indicator of life—because we breathe it—although a planet can fill up with that gas in less lively ways. On Mars, researchers have been psyched by puffs of methane, organic molecules, and the release of gas after soil was fed a solution of what we on Earth call nutrients, perhaps indicating metabolism. They create terms like "the Goldilocks zone" for the regions around stars where planets could host liquid water, implying that what's just right for Earth life is also just right everywhere else.

Even when scientists do discover biology unfamiliar to them, they tend to relate it to something familiar. For instance, when Antonie van Leeuwenhoek saw single-celled organisms through his microscope's compound lens in the 17th century, he dubbed them "animalcules," or little animals, which they are not.

Heather Graham, who works at NASA's Goddard Space Flight Center and is LAB's deputy principal investigator, sees van Leeuwenhoek's discovery as a successful search for LAWDKI, close to home. The same description applies to scientists' discovery of Archaea, a domain of ancient single-celled organisms first recognized in the 1970s. "If you reframe those discoveries as agnostic biosignatures in action, you realize that people have been doing this for a while," Graham says.

Around 2016, Johnson joined their ranks, finding some like-minded nonbelievers who wanted to probe that darkness. At an invitation-only NASA workshop about biosignatures, Johnson sat at a table with scientists like Graham, gaming out how they might use complexity as a proxy for biology. On an exaggerated macroscale, the idea is that if you come across a fleet of 747s on Mars, you might not know where they came from, but you know they're unlikely to be random. Someone, or something, created them.

After the meeting, Johnson and her co-conspirators put in a last-minute proposal to develop an instrument for NASA. It would find and measure molecules whose shapes fit physically together like lock and key because that rarely happens in random collections of chemical compounds but pops up all over living cells. The instrument idea, though, didn't make the cut. "That's when we realized, 'Okay, we need to roll this back and do a lot more fundamental work,'" Graham says.

The space agency would give them a chance to do so, soon putting out a call for "Interdisciplinary Consortia for Astrobiology Research." It promised multiple years of funding to dig deeper into Johnson and her associates' lunch-table ideas. They needed a larger team, though, so they pinged planetary scientists, biologists, chemists, computer scientists, mathematicians and engineers—some space-centric to the core and oth-

> **What if extraterrestrial life didn't have DNA or RNA or other nucleic acids? What if their cells got instructions in some other biochemical way?**

ers, Johnson says, "just beginning to consider the astrobiology implications of their work." It was particularly important to do this now because researchers are planning to send life-detection instruments to destinations such as the solar system moons Europa, Enceladus and Titan, more exotic than most of the worlds visited so far. "Most of these other places we're beginning to think about as targets for astrobiology are really weird and different," Johnson says. If you're going to a weird and different place, you might expect weird and different life, squirming invisibly beyond the reach of a lamppost's light.

Their pitch worked: The expanded lunch table became LAB. Now the project, a spread-out coalition of scientists more than a single physical laboratory, is a few years deep into its work. The researchers aim to learn how things like the complexity of a surface, anomalous concentrations of elements and energy transfer—such as the movement of electrons between atoms—might reveal life as no one knows it.

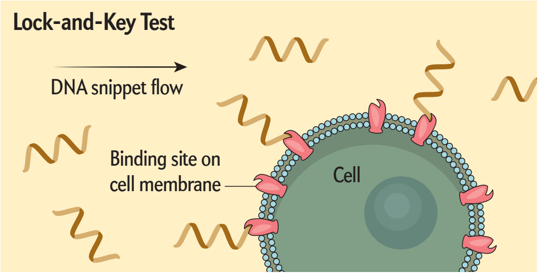
LAB WORK

LAB'S RESEARCH is a combination of fieldwork, lab projects and computation. One project is a planned visit to Canada's Kidd Creek Mine, which drops nearly 10,000 feet into the ground. Its open pit looks like a quarry reaching toward the seventh circle of hell. At those depths, around 2.7 billion years ago, an ocean floor brewed with volcanic activity, which left sulfide ore behind. The conditions are similar(ish) to what astronomers believe they might find on an "ocean world" like Europa. In the mine, the scientists hope to probe the differences between minerals that formed by crystallization—when atoms fall out of solution and into an ordered, lattice structure in the same place they are now—and evidence of biology.

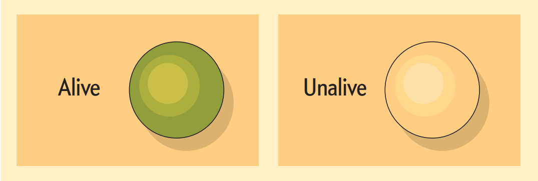
The two kinds of materials can look superficially alike because they're both highly ordered. But the team aims to show that geochemical models, which simulate how water saturated with chemicals will precipitate them out, will predict the kind of abiotic crystals found there. Kidd Creek, for instance, has its own sort: Kiddcreekite, a combination of the copper, tin, tungsten and sulfur that crystallizes from the water. Those same models, however, aren't likely to predict biological structures, which form according to different forces and rules. If that turns out to be true, the models may prove useful when applied to alien geochemical conditions to predict the naturally forming minerals. Anything else that's found there, the thinking goes, might be alive.

Johnson is reaching back to her postdoc days, using the genetic sequencers whose relevance she called into question back then. The group, though, has found a way to make them more agnostic. The researchers plan to use the instruments to investigate the number of spots on a cell's surface where molecules can attach themselves—like the places where antibodies stick to cells. "We had this hypothesis that there are more binding sites on something complicated like a cell than a small particle," Johnson says, such as an unalive mote of dust. Something alive, in other words, should have more lock-and-key places.

To test this idea, they create a random pool of DNA snippets and send it toward a cell. Some snippets will hook up with the cell's exterior. The scientists next remove and collect the bound snippets, then capture the unbound snippets and send them back to the target cell again, repeating the process for several cycles. Then they see what's left at the end—how much has hooked on and how much is still free. In this way, the researchers can compare the keys locked into the cell with those attached to something like a dust particle.



The scientists will also scrutinize another key difference they suspect divides life and not-life: Things that are not alive tend to be at a kind of equilibrium with their environment. In contrast, something that's alive will harness energy to maintain a difference from its surroundings, LAB member Peter Girguis of Harvard hypothesizes. "It's using power to keep ourselves literally separate from the environment, defining our boundary," he says. Take this example: When a branch is part of a tree, it's alive, and it's different—in a bordered way—from its environment. If you remove that life from its energy source—pluck the branch—it dies and stops using power. "In a matter of time, it disintegrates and becomes indistinguishable from the environment," Girguis says. "In other words, it literally goes to equilibrium."



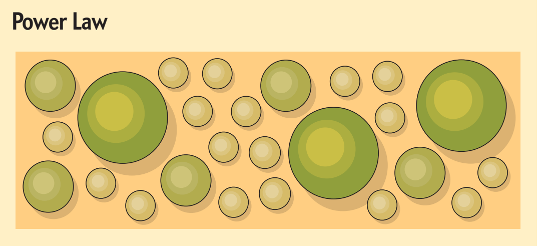
The disequilibrium of living should show up as a *chemical* difference between an organism and its surroundings—regardless of what the surroundings, or the life, are made of. "I can go scan something, make a map and say, 'Show me the distribution of potassium,'" Girguis says. If blobs of concentrated K appear, dotting the cartography only in certain spots, you may have biology on your hands.

Girguis's LAB work intertwines with another pillar of the group's research: a concept called chemical fractionation, which is how life preferentially uses some elements and isotopes and ignores others. A subgroup investigating this idea, led by Christopher House of Pennsylvania State University, can use the usual data that space instruments take to suss out the makeup of a planet or moon. "If you understand the fundamental rules about the inclusion or exclusion of elements and isotopes, then you can imagine a different ecosystem where it still behaves by similar rules, but the elements and isotopes are totally different," House says. It could give disequilibrium researchers a starting point for which kinds of patterns to focus on when making their dotted maps.

Within House's group, postdoc researchers are studying sediments left by ancient organisms in Western Australia. Looking at these rock samples, they try to capture patterns showing which elements or isotopes early Earth life was picky about. "We're hopeful that we can start to generalize," House says.

LAB's computing team, co-led by Chris Kempes of the Santa Fe Institute, is all about such generalizing. Kempes's research focuses on a concept called scaling—in this case, how the chemistry inside a cell changes predictably with its size and how the abundance of different-sized cells follows a particular pattern. With LAB, Kempes, House, Graham and their collaborators published a paper in 2021 in the *Bulletin of Mathematical Biology* about how scaling laws would apply to bacteria. For instance, if you sort a sample of biological material by size, differences pop out. Small cells' chemistry looks a lot like their environment's. "The bigger cells will be more and more different from the environment," Kempes says.

The abundance of cells of different sizes tends to follow a relationship known as a power law: Lots of small things with a steep drop-off as cells get larger. If you took an extraterrestrial sample, then, and saw those mathematical relationships play out—small things that looked like their surroundings, with progressively larger things looking less like their environments, with lots of the former and few of the latter—that might indicate a biological system. And you wouldn't need to know ahead of time what either "environment" or "biology" looked like chemically.

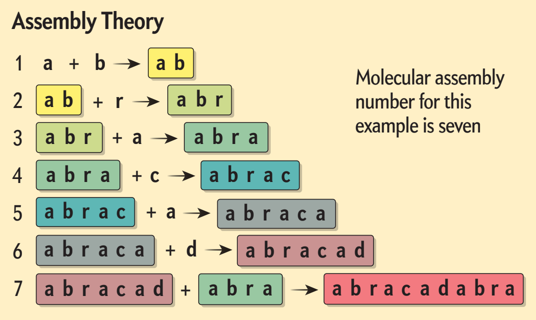


Power Law

Cronin, a sort of heretic within this heretic group, has his own idea for differentiating between living and not. He's an originator of something called assembly theory, a "way of identifying if something is complex without knowing anything about its origin," he says. The more complex a molecule is, the more likely it is to have come from a living process.

That can sound like a bias in the agnosticism, but everyone generally concedes that life results from, as Sutherland puts it, "the complexification of matter." In the beginning, there was the big bang. Hydrogen, the simplest element, formed. Then came helium. Much later there were organic molecules—conglomerations of carbon atoms with other elements attached. Those organic molecules eventually came together to form a self-sustaining, self-replicating system. Eventually that system started to build the biological equivalent of 747s (and then actual 747s).

In assembly theory, the complexity of molecules can be quantified by their "molecular assembly number." It's just an integer indicating how many building blocks are required to bond together, and in what quantities, to make a molecule. The group uses the word "abracadabra" (magic!) as an example. To make that magic, you first need to add an *a* and a *b*. To that *ab,* you can add *r*. To *abr,* toss in another *a* to make *abra*. Then attach a *c,* then an *a* and then a *d,* and you get *abracad*. And to *abracad,* you can add the *abra* that you've already made. That's seven steps to make *abracadabra,* whose molecular assembly number is thus seven. The group postulated that a higher number meant a molecule would have a more complicated "fingerprint" on a mass spectrometer—a tool that separates a sample's components by their mass and charge to identify what it's made of. A complex molecule would show more distinct peaks of energy, in part because it was made of many bonds. And those peaks are a rough proxy for its assembly number.



Assembly Theory

Cronin had bragged that by doing mass spectrometry, he could measure the complexity of a molecule without even knowing what the molecule was. If the technique indicated that a molecule's complexity crossed a given threshold, it probably came from a biological process.

Still, he needed to prove it. Through LAB, NASA gave him double-blind samples of material to yea or nay as biological. The material hailed from outer space, fossil

Scientists have gone from thinking "if you see oxygen on a planet, slam dunk," to thinking "there are no slam dunks."

beds and the sediments of bays, among other places. One of the samples was from the Murchison meteorite, a 220-pound hunk of rock, full of organic compounds. "They thought the technique would fail because Murchison is probably one of the most complex interstellar materials," he says. But it succeeded: "It basically says Murchison seems a bit weird, but it's dead."

Another sample contained 14-million-year-old fossils, sculpted by biology but meant to fool the method into a "dead" hit because of their age. "The technique found that they were of living origin pretty easily," Cronin says. His results appeared in *Nature Communications* in 2021 and helped to convince Cronin's colleagues that his line of research was worthy. "There are a lot of skeptical people in [LAB's] team, actually," he says.

ALIENS DISCOVERED??

THERE IS PLENTY of skepticism outside LAB as well. Some scientists question the need to search for unfamiliar life when we still haven't done much searching for extraterrestrial life as we know it. "I think there's still a lot we can explore before we go to life as we don't know it," says Martina Preiner of the Royal Netherlands Institute for Sea Research and Utrecht University.

Still, even among old-school astrobiology researchers looking for Earth-like signatures on exoplanets, the LAB approach has support. Victoria Meadows of the University of Washington has been thinking about such far-off signals for two decades. She's seen the field change over that time—complexify, if you will. Scientists have gone from thinking "if you see oxygen on a planet, slam dunk," to thinking "there are no slam dunks." "I think what my team has helped provide and how the field has evolved is this understanding that biosignatures must be interpreted in the context of their environment," she says. You have to understand a planet's conditions, and those of its star, well enough to figure out what oxygen might *mean*. "It may be that the environment itself can either back up your idea that oxygen is due to life or potentially that the environment itself may produce a false positive," she says, such as from an ocean boiling off.

In a lot of ways, Meadows says, looking for agnostic biosignatures is the ultimate way to take such cosmic conditions into account. "You have to understand the environment exquisitely to be able to tell that something anomalous—something that isn't a planetary process—is operating in that environment," she says. Still, this variety of alien hunting is in its infancy. "I think they're really just starting off," she says. "I think what LAB is doing in particular is a pioneering effort on really getting some science under this concept."

Even so, Meadows isn't sure how likely LAWDKI is. "The question is, 'Is the environment on a [terrestrial] extrasolar planet going to be so different that the solutions are so different?'" Meadows asks. If the conditions are similar and the chemicals are similar, it's reasonable to think life itself will be similar. "We are expecting to see some similar science if these environments are similar, but of course I will expect that there'll be things that will surprise us as well." It's for all these reasons that Meadows, whose work focuses on exoplanets, is working with the LAB scientists, whose research for now homes in on the solar system, to bring their two worlds together.

By the end of LAB's grant, the team plans to develop instruments that will help spacecraft notice weird and different life close to home. "We're extremely focused on the ultimate goal—how we can take these tools and techniques and help develop them to the point they can become instruments on space missions," Johnson says.

No one piece of information, gathered from a single instrument, can reliably label something life, though. So the group is working toward suites of devices, drawing on all their focus areas, that work together in different environments, such as worlds wrapped in liquid versus rocky deserts. Graham is gathering sample sets that LAB's subgroups can test in a round-robin way to see how the superimposition of their results stacks up. They might look for, say, molecules with big assembly numbers concentrated in bounded areas that look different from their environment.

Even if these approaches collectively find something, it's unlikely to provide a definitive answer to the question "Are we alone?" It will probably yield a "maybe," at least for a while. That grayness may disappoint those who'd like "Aliens discovered!" headlines, instead of "Aliens discovered?? Check back in 10 years."

"I understand that frustration," Johnson says, "because I'm a restless sort of person." That restlessness relates in part to her own mortality. The end of the time when she's out of equilibrium with her environment. The demise of her complexity, of her detectability and ability to detect. "We have these ephemeral lives," she says. "We have this world that's going to end. We have this star that's going to die. We have this incredible moment. Here we are: alive and sentient beings on this planet." All because, at some point, life *started*.

That may have happened tens or hundreds or thousands or millions or billions of other times on other planets. Or, maybe, it has only happened here. "It just feels," Johnson says, "like an extraordinary thing that I want to know about the universe before I die."

FROM OUR ARCHIVES

The Search for Extraterrestrial Life. Carl Sagan; October 1994.

scientificamerican.com/magazine/sa

PRAIRIE VOLES are unusual among rodents in choosing a single partner with whom they share a nest and raise their young. Their monogamous bond may last a lifetime.

ANIMAL BEHAVIOR

The Neurobiology of Love

Prairie voles are providing surprising new insights into how social bonds form

By Steven Phelps, Zoe Donaldson and Dev Manoli

Photograph by Aubrey M. Kelly

Steven Phelps is director of the Center for Brain, Behavior and Evolution at the University of Texas at Austin. He studies rodents with unusual social behaviors to understand how brains, genes and the environment interact to produce complex behaviors.

Zoe Donaldson is a behavioral neuroscientist at the University of Colorado Boulder. She uses gene therapy vectors and advanced neural technologies to understand how species form pair-bonds, how bonding changes the brain and how we overcome loss.

Dev Manoli is a psychiatrist at the University of California, San Francisco. His laboratory has pioneered the use of CRISPR to manipulate vole genomes to understand how the brain encodes attachments and how these processes are altered in neuropsychiatric illnesses.

THE PRAIRIE VOLE IS A SMALL MIDWESTERN RODENT KNOWN FOR SHACKING UP and settling down, a tendency that is rare among mammals. Mated pairs form bonds, share a nest and raise young together. In the laboratory, a pair-bonded vole will work for access to its mate. Prairie voles even exhibit something like empathy for their partners, getting stressed when they are stressed, and consoling each other through touch. As the pandemic has brought into stark relief, such social connections are essential to human well-being as well. Researchers are turning to these unusual rodents to understand how relationships have a profound impact on health.

Leveraging biomedical advances of the past few decades, scientists have watched neurons in action. They have manipulated gene activity with exquisite precision, examining the functions of individual genes in specific brain regions. With the prairie vole as a subject, researchers are learning how bonds are forged, how early life shapes relationships and why we ache when they fall apart.

Of course, prairie voles are not humans. And so these insights raise a question. How has a shaggy little rodent slightly smaller than a tennis ball and routinely mistaken for a mole, a mouse or a rat become a stunt double for the thrills of love and the perils of loss? The answer tells us as much about how science advances as it does about our own hearts.

EARLY CLUES

OVER THE PAST two million years huge sheets of ice ground the landscape of central Illinois to a whetstone flatness. Today cornfields stretch to the horizon, but crowded into their interstices are fragments of the prairie that once covered this part of the state. One autumn nearly 50 years ago Lowell Getz, then a young ecologist at the University of Illinois, checked traps hidden in the grass and clover. One of the rodent species he captured, the prairie vole, behaved differently from the others, he noticed. Specific pairs of males and females kept showing up in traps together. In the 1970s zoologist Devra Kleiman had estimated that only about 3 percent of mammal species are monogamous. The data Getz and his students gathered suggested the prairie vole was among them.

Getz was not the first to suggest that prairie voles were monogamous, but his work attracted the attention of a colleague, behavioral endocrinologist Sue Carter, and together their research teams began to document the full range of vole social behaviors and the hormones that underpin them both in the lab and in the wild. Through studies carried out in the 1980s and 1990s, they found that males and females share a nest, raise young and defend a territory together. Carter's lab developed a simple behavioral test to assess a vole's "partner preference" that involved tethering a mate in one small chamber and an unfamiliar vole in another and then allowing a vole to choose between a partner and a stranger. Bonded prairie voles prefer to cuddle with a mate. Their bonds, which can last a lifetime, emerge after scandalously extensive mating.

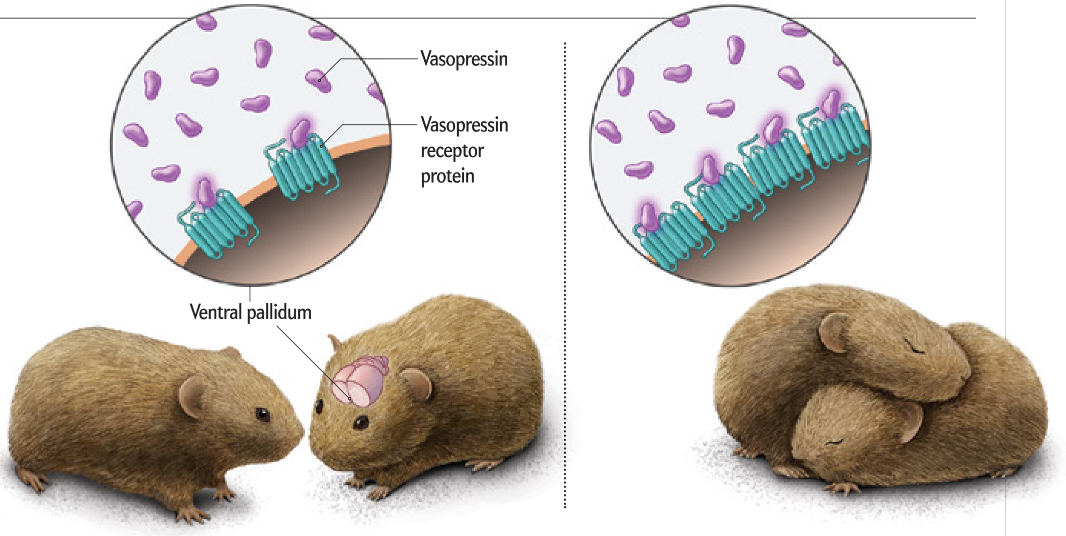
Getz attributed the evolution of prairie vole bonding to the sparse distribution of food resources in their uniformly flat and grassy environment, which led to the wide scattering of voles across the landscape. Under such conditions, males were unable to reliably pursue multiple females, as other rodent species do, so it made more sense to settle down with one partner and defend a shared home. Females gained a partner to help with parental care and stave off intruders. Carter's group found that the hormone oxytocin, long known as a regulator of birth, lactation and maternal care, was essential to forming bonds. A related hormone, vasopressin, soon emerged as another crucial regulator of prairie vole bonding.

Forming Bonds

Studies of the monogamous prairie vole and the promiscuous meadow vole have illuminated the neurobiology of bonding. The work has identified hormones and their receptors that shape social connections, as well as brain regions and specific neural circuits involved in attachment.

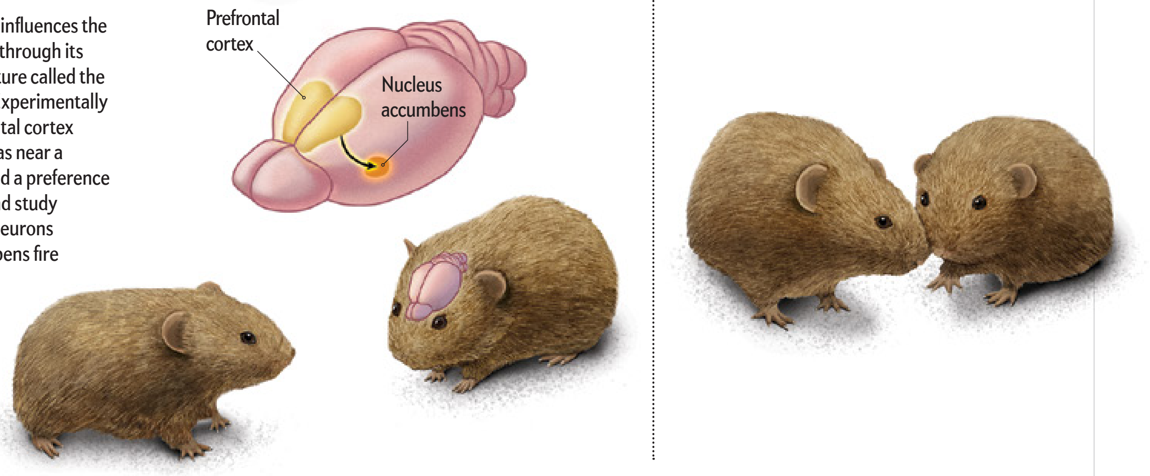
Case Study 1

The hormone vasopressin, a regulator of prairie vole bonding, is also present in the meadow vole. But prairie voles have an abundance of these receptors in the brain's ventral pallidum, unlike meadow voles. When researchers delivered an extra copy of the vasopressin receptor gene to the ventral pallidum of meadow voles, these normally solitary and promiscuous voles gained a propensity for cuddling.



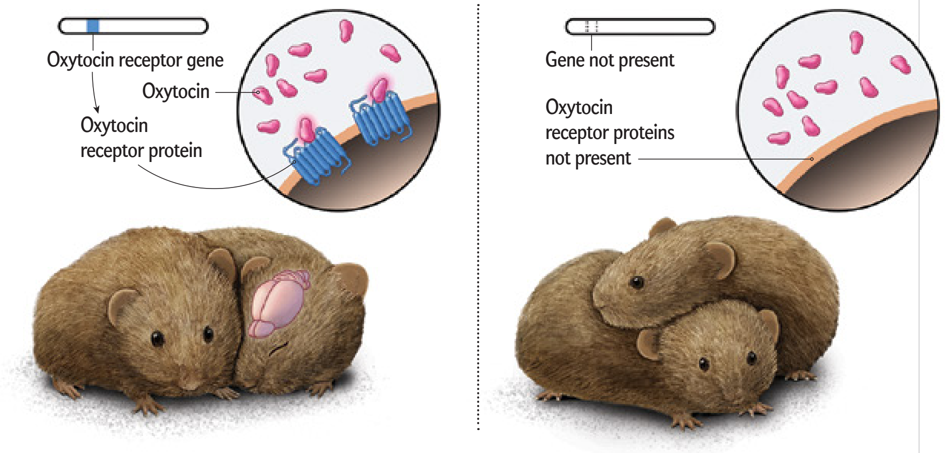
Case Study 2

The prefrontal cortex influences the brain's reward circuit through its connection to a structure called the nucleus accumbens. Experimentally activating the prefrontal cortex when a prairie vole was near a potential mate induced a preference for that mate. A second study showed that reward neurons in the nucleus accumbens fire just before an animal approaches a mate. The number of neurons that respond to a mate increases as the bond deepens.



Case Study 3

The hormone oxytocin has long been considered crucial for the formation of bonds in prairie voles—and humans. Surprisingly, voles genetically engineered to lack oxytocin receptors did not show any impairments to their ability to connect with a mate. Researchers do not yet know how the voles can bond in the absence of oxytocin receptors, but it may be that other genes or neural pathways compensate.



Graphic by Mesa Schumacher

Oxytocin, vasopressin, and other closely related hormones are ubiquitous in nature. They have been found in nearly every animal species examined. But if these hormones occur in such a wide range of species, many of which are not monogamous, then their presence alone is surely not enough to make a species form pair-bonds. So how and why do these hormones shape bonding?

The answer lies in the way that hormones bring about changes in the brain. Hormones are small chemical compounds; in the case of vasopressin and oxytocin, they are small proteins known as peptides. Hormones influence the functions of the body's cells by binding to large proteins known as receptors, whose shape and electrical charge interact with one particular hormone. When a hormone binds to its receptor protein, it causes a change in the receptor's shape that triggers changes within the cell.

Because oxytocin and vasopressin are present in many species but promote bonding only in some species, it seemed plausible that there might be species differences in the distribution of hormone receptors. In the 1990s Tom Insel of the National Institutes of Health and his colleagues discovered that prairie voles and their monogamous relatives, pine voles, have receptors for oxytocin and vasopressin in different brain regions than their promiscuous relatives, the meadow and montane voles. Whereas the monogamous voles have abundant receptors for these hormones in the nucleus accumbens and the ventral pallidum, structures that are part of the brain's reward circuit, promiscuous voles largely lack receptors in these brain areas. These are the same regions neuroscientists have long studied in the context of drug abuse. Headlines soon announced that love was addictive.

The findings supported the idea that differences in the distribution of hormone receptors could account for the different behaviors of promiscuous and monogamous voles. But to understand exactly how hormone receptors shape bonding, researchers needed to manipulate the genes that encode the receptors. The tools for doing that kind of work would come from an unexpected source.

NEW TOOLS, NEW REVELATIONS

IN THE LATE 1960S, even before ecologists were starting to wonder about the social lives of prairie voles, virologists made a discovery that would eventually lead to the development of a novel tool for studying genes, brains and behavior. The scientists were examining the DNA of a group of viruses called adenoviruses, which cause the common cold. They found that their adenovirus samples were contaminated by viruslike particles that they called adeno-associated viruses (AAV). Whereas viruses need a host cell to reproduce, an AAV needs both a cell and the co-infection of an adenovirus to multiply. It's a parasite's parasite. If an AAV infects a human cell that lacks an adenovirus, it simply lies in wait until one comes along.

The fact that an AAV can enter and live peaceably inside a cell makes it an excellent vector for delivering DNA to change a cell's workings. In the 1990s researchers began engineering AAV to tweak the neurons of rats and mice in an effort to figure out what they do. The tools they developed, we soon learned, worked just as well on voles. To study the role of hormones in pair-bonds, Larry Young of Emory University and his colleagues used AAV to deliver an extra copy of the vasopressin receptor gene into the ventral pallidum of meadow voles. With their vasopressin receptor levels boosted in this brain region, these normally solitary and promiscuous voles gained a new propensity to cuddle with a mate. The work showed that the abundance of vasopressin receptors in the brain's reward circuits explained at least some of the behavioral differences between monogamous and promiscuous voles.

AAV has also allowed researchers to actually watch bond formation in real time. When scientists engineered a novel light-activated protein that could alter the electrical activity of a neuron, neurobiologists used an AAV to put this protein into the prefrontal cortex, a brain region that influences reward through its contact with the nucleus accumbens. Elizabeth Amadei, Robert Liu and their colleagues at Emory University showed that activating these neurons when a vole was near a potential partner was enough to generate a preference for the would-be mate. Another group, led by one of us (Donaldson), used AAV to introduce a protein that glows when a neuron is active into the brains of voles. Using tiny head-mounted microscopes, the researchers could see what was happening in the brain as voles formed a bond. They found that reward neurons in the nucleus accumbens light up just before an animal approaches a mate. Remarkably, the number of neurons that respond to a mate also increases as a bond deepens over time.

The advent of CRISPR DNA-editing technology a decade ago has given investigators new and unprecedented control over genes and the work they do. CRISPR, an acronym for clustered regularly interspaced short palindromic repeats, operates like a molecular scalpel to make incisions in DNA. Tailoring genomes with CRISPR is complex and costly, but the technology has also upended our understanding of oxytocin, the so-called love hormone.

Decades of research implicates oxytocin in the formation of prairie vole pair-bonds. And several studies suggest that oxytocin acts in reward circuits to shape human bonds as well. It seemed a promising experiment, then, when one of us (Manoli) teamed up with colleagues to use CRISPR to delete the gene that encodes the oxytocin receptor in prairie vole embryos. We expected the genetically modified voles to exhibit impairments in their ability to bond with mates. But shockingly, prairie voles that lacked the oxytocin receptor altogether actually formed preferences for mates as readily as their genetically unmanipulated siblings.

How can this be? Honestly, we don't yet know. One idea is that during development other genes or neural pathways naturally compensate for the lack of oxytocin receptors. We already know that there are many other genes that influence pair-bonding, not only oxytocin, vasopressin and their receptors. The use of CRISPR has revealed that a piece of music we imagined had been written for a small group is really a symphony. Transcribing this new, more complex music will deepen our understanding of attachment and its underlying mechanisms.

BEYOND OXYTOCIN AND VASOPRESSIN

THE DISCOVERY that the oxytocin receptor is not strictly necessary for prairie vole bonding demonstrates that however important the genes encoding oxytocin, vasopressin and their receptors may be, they are not the whole story. Other 21st-century tools are helping scientists fill in the gaps in our understanding of how social connections form—and how they rewire the brain.

The past decade of work in gene sequencing has made it possible to exhaustively quantify the genes that are active in any particular brain region. This genome-wide approach to looking for genes and other DNA sequences associated with certain behaviors has its own challenges, but it offers a view that is "unbiased" in the sense that it looks beyond the small set of players scientists already think are important for bonding.

One such study examined gene activity across brain regions during bond formation. It found that most differences between the monogamous prairie vole and the promiscuous meadow vole were evident even before bonding began, as though their brains were already prepared for their specific social behaviors. After the voles had mated repeatedly, a subset of genes turned on that are particularly important for learning and memory—the kind of rewiring one might expect to happen as an animal transitions from being single to being paired with a specific partner. Another study found that distinctive genes are turned on in the brain's reward structures as the bond becomes stable. These changes reverse if the bond is broken by prolonged separation.

Just as new genome sequencing methods have offered fresh perspectives on DNA and its function, parallel advances in the microscopic study of biological tissues have expanded our view of the brain. Traditionally, studying the microanatomy of tissue has required that investigators obtain a thin slice of tissue for examination. We can now render a tissue transparent, allowing researchers to image an entire brain without the need to physically slice it. Like genome-wide studies, this approach to studying the brain offers an unbiased view. By examining cleared brains for a protein that is produced in response to neural activity, one of us (Phelps), along with Pavel Osten, then at Cold Spring Harbor Laboratory, and other colleagues, made the first brain-wide map of regions that are active as prairie voles turn mating into bonds. The results confirm earlier work suggesting that reward circuits are involved in bonding but also implicate many other brain regions. They show that in both males and females, neural activity follows a path known to be important in sexual responses. This neural pathway finds its way into nearly 70 distinct brain regions, eliciting a storm of activity as brains rewire themselves for a bond. And just as Sue Carter suggested decades ago, sex itself seems to drive this rewiring.

Once a bond has developed, the neural activity is concentrated in a much smaller circuit. Connections between the amygdala and hypothalamus, brain regions essential to both emotional learning and hormone release, come alive. These same connections have recently been shown to shape nonsexual social connections in lab mice, and the new results suggest some common mechanisms of social attachments across both species and categories of bonds. Together these unbiased approaches promise a complete catalog of the genes and brain regions that enable a bond to form and persist or that allow it to dissolve in time.

FROM VOLES TO HUMANS

IN THE MIDDLE of the 20th century British psychologist John Bowlby and American-Canadian psychologist Mary Ainsworth drew on the work of animal behaviorists to suggest that a child's need for love was fundamental to human biology. Bowlby posited that our attachments represented a specialized evolved neural system—that is, an evolutionarily adaptive brain mechanism that helped us successfully navigate childhood by binding us to our caregivers. Although Bowlby and Ainsworth's attachment theory was considered radical in its time, scientists have since expanded it to explain not only human parenting but also friendships, romantic relationships and the pang of their loss.

Prairie vole bonds and the mechanisms that underlie their formation and influence provide a concrete example of what such an evolved neural system might look like. We see that bonds rely on joining the specific cues associated with a potential partner to the feelings of desire. Reward prompts voles to stay close to each other, to huddle together. There are genes that stand ready to guide circuits toward learning the identity of a new partner, genes that seem to stabilize bonds, and genes that oversee the experience of loss. To do so, they must, in ways we do not yet fully understand, harness the brain's capacity for memory and emotion.

This is not to say that the vole's experience of pair-bonding is exactly like the human experience of love. Neuropsychologists have built on the framework derived from prairie vole research to suggest that centers of emotion and reward interact with other brain regions—areas that promote empathy and perspective taking, for example—to produce the rich sense of what it means to be in love. The view implies that romantic love has an emotional core similar to that experienced by other animals but enriched by our complex understanding of ourselves and our most significant others.

Human studies inspired by prairie vole findings support the comparison of the two species. Love is so essential to the human experience that scientists long assumed its biological basis must reside in our cerebral cortex, the brain's presumed center of thought. This part of the brain expanded considerably during primate evolution, which suggests that it has played an important role in the success of our branch of the mammal family tree. Work on prairie voles, however, inspired neuropsychologists to look at more ancient structures, in the same reward regions implicated in prairie vole bonding. In one study, scientists asked people in relationships to rate just how in love they were with a partner. They found that these ratings predicted how much blood flowed to their reward systems when viewing pictures of their partners. Likewise, when a human subject holds her partner's hand, it activates her nucleus accumbens—one of the brain regions that in prairie voles has receptors for oxytocin and vasopressin.

Our understanding of the hormonal regulators of human affections also seems consistent with our understanding of prairie vole pair-bonding. Humans get a flush of oxytocin in response to a tender caress or to orgasm. But it's a versatile hormone: it also surges when we make eye contact with a large-eyed puppy.

Scientists hope to one day grasp human bonding well enough to be able to intervene when it causes pain—to lessen, for example, the ravages of chronic loneliness or to dull the edges of a devastating grief. Drugs intended to mimic the functions of oxytocin and vasopressin have, so far, not lived up to their therapeutic potential. And as we have seen, even among prairie voles the mechanisms of bonding are not entirely understood.

To fully comprehend bonds and their consequences, we need science rich enough to accommodate ecology, evolution, neuroscience and molecular genetics, each of which offers a complementary view on how and why bonds form. It requires basic research. The same technological advances that have made the prairie vole such an exciting animal in which to study attachment are opening up new avenues of study in other species, such as the parental care of poison frogs and the conversations of fruit bats. The knowledge generated from such studies is valuable for its own sake, and what we discover may one day transform our lives. New species and new tools mean new perspectives on life—and love. SA

FROM OUR ARCHIVES

Powers of Two. Blake Edgar; September 2014.

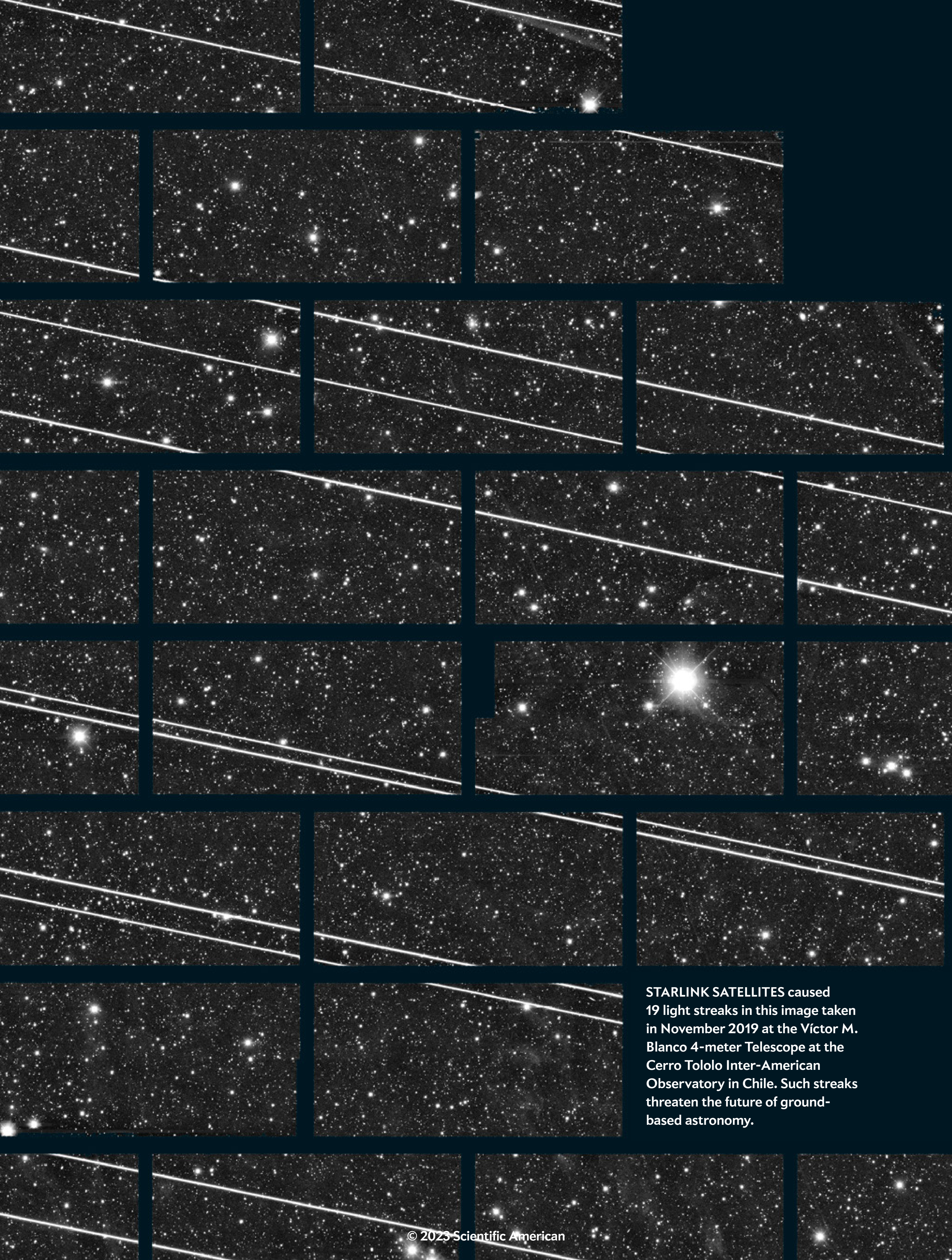
scientificamerican.com/magazine/sa

ASTRONOMY

The Threat of Satellite Constellations

Growing swarms of spacecraft in orbit are outshining the stars, and scientists fear no one will do anything to stop it

By Rebecca Boyle



STARLINK SATELLITES caused 19 light streaks in this image taken in November 2019 at the Víctor M. Blanco 4-meter Telescope at the Cerro Tololo Inter-American Observatory in Chile. Such streaks threaten the future of ground-based astronomy.

Rebecca Boyle is an award-winning freelance journalist in Colorado. Her forthcoming book *Walking with the Moon: Uncovering the Secrets It Holds to Our Past and Our Future* (Random House) will explore Earth's relationship with its satellite throughout history.

RACHEL STREET FELT FRIGHTENED AFTER A RECENT PLANNING MEETING FOR THE VERA C. RUBIN Observatory. The new telescope, under construction in Chile, will photograph the entire sky every three nights with enough observing power to see a golf ball at the distance of the moon. Its primary project, the Legacy Survey of Space and Time, will map the galaxy, inventory objects in the solar system, and explore mysterious flashes, bangs and blips throughout the universe. But the telescope may never achieve its goals if the sky fills with bogus stars. New swarms of satellite constellations, such as SpaceX's Starlink, threaten to outshine the real celestial objects that capture astronomers' interest—and that humans have admired and pondered for all of history. "The more meetings I attend about this, where we explain the impact it is going to have, the more I get frightened about how astronomy is going to go forward," says Street, an astronomer at Las Cumbres Observatory in California. As one astronomer mentioned moving up observations in the telescope's schedule, a sense of foreboding fell over her. Her colleagues were talking about making basic observations early because at some point, it might be too late to do them at all. "That sent a chill down my spine," Street recalls.

As low-Earth orbit fills with constellations of telecommunications satellites, astronomers are trying to figure out how to do their jobs when many cosmic objects will be all but obscured by the satellites' glinting solar panels and radio bleeps. Recent reports from the Rubin Observatory team and from the U.S. Government Accountability Office (GAO) describe a dire situation in which astronomy—the first science—comes under direct threat. Astronomers say that if unchecked, satellite constellations will jeopardize not just the Rubin Observatory's future but almost any campaign to observe the universe in visible light. "It is somewhere in the range of very bad to terrible," says Jonathan McDowell, an astronomer at the Center for Astrophysics | Harvard & Smithsonian who tracks satellites. How bad depends on how many satellites launch in coming years and how bright they are. "A few thousand satellites are a nuisance, but hundreds of thousands is an existential threat to ground-based astronomy."

Telescope project managers are rewriting scheduling programs to avoid the new satellite swarms, but that already impractical task will grow impossible as the number of spacecraft in low-Earth orbit keeps rising. Astronomers are trying to write software to eliminate bright satellite streaks from their all-sky images. But this, too, will be futile if the newest planned satellites make it to orbit; they are so bright that they threaten the electronics of telescope cameras. People who study phenomena as diverse as colliding black holes and near-Earth asteroids worry their work will become impossible. Astronomers talk about the satellite swarms in increasingly ominous terms. "As Chicken Little said, the sky is falling. But instead of one acorn, I think it really is falling," says Anthony Tyson, an astronomer at the University of California, Davis, and chief scientist for the Rubin Observatory. When it comes to sounding the alarm, "it is probably very high time. I might even say almost too late."

CTIO (*preceding pages*)

THE FIRST ARTIFICIAL SATELLITE was Sputnik 1, launched by the Soviet Union in October 1957, and now more than 5,400 satellites orbit Earth at any given time. More than half are owned by U.S. companies or agencies, according to a database maintained by the Union of Concerned Scientists. Most satellites are in low-Earth orbit, less than 1,200 miles above the ground. These satellites, including the International Space Station, make a full orbit every hour and a half or so.

Beginning in May 2019, SpaceX started populating those orbital planes with hundreds of its Starlink satellites, designed for broadcasting Internet and cell phone service around the globe. As of December 2022, 3,268 of all satellites orbiting Earth—more than half—were Starlink, according to McDowell's tracking efforts. The spacecraft are launched in groups and orbit Earth in patterns, called constellations, that enable them to work together. Both the number of satellites and their brightness pose problems for astronomy. They are most visible soon after they launch, glinting across the twilight sky like a tiny dazzling train. To the digital cameras on telescopes, they appear as bright streaks of light, blocking stars and astronomical objects while overexposing the entire field of view. "It's like you're driving down the road and you're looking out through your windshield, and there's this oncoming car with its brights on," Tyson says. "You lose a lot of information—not just at the position of those headlights but all over, and your eyes are overexposed, too."

The $700-million Rubin Observatory is uniquely threatened among ground-based astronomy projects. The telescope is scheduled for first light in 2024, and by then tens of thousands of satellites, including the Starlink constellation and others, could be orbiting Earth. The observatory's planned Legacy Survey of Space and Time will use an 8.4-meter telescope combined with a 3.2-gigapixel digital camera—the largest ever built—to capture 1,000 images of the sky every night for a decade. Each image will cover 9.6 square degrees of sky, which is about 40 times the area of the full moon. The telescope is meant to find new and potentially threatening near-Earth objects, as well as transient events such as supernovae—and things no one has thought of yet, as Tyson puts it. But these observations could be "significantly degraded by the alarming pace" of new satellite deployments, according to an analysis written primarily by Tyson and posted last August by the Rubin Observatory team.

Another report, prepared by the GAO and sent to Congress on September 29, found that the satellite constellations could harm astronomy and cause environmental impacts as they fall back through Earth's atmosphere. "As more satellites are deployed into [low-Earth orbit], nearly all facets of optical astronomy may be negatively affected," the GAO wrote. In a subsequent report released November 2, the watchdog agency urged the FCC (which regulates satellite communications in the U.S.) to more thoroughly investigate the environmental effects of large satellite constellations and reconsider the standards required for their licensing. But many astronomers worry such rules won't come soon enough, or be stringent enough, to save ground-based astronomy.

The first and most prominent provider of these satellite swarms is SpaceX, which is also the only company, so far, to publicly work with astronomers to try to dim its satellites. The company has created DarkSat, a light-absorbing darker satellite, as well as antireflective coatings for solar panels. (SpaceX did not respond to a request for comment.) Between SpaceX and other companies, such as British satellite provider OneWeb and a Chinese company called Galaxy Space, more than 4,000 satellites designed for constellationlike networked coverage are now in orbit. According to permits filed with the world's two leading telecommunications agencies—the U.S. Federal Communications Commission and the International Telecommunication Union (ITU)—a combined 431,713 satellites in 16 constellations are planned to launch in the coming years.

The satellite companies point out that more than one third of the world's population—some 2.9 billion people, according to a 2021 ITU report—has still never used the Internet. Constellations of communications satellites could change that. But light from the Starlink constellation alone will add streaks to at least 30 percent of images made from the Rubin Observatory. If 400,000 satellites make it to orbit, every image taken in the early evening will have a streak. The OneWeb constellation will orbit at a higher elevation than other constellations, so it will be visible all night long during certain times of year. (OneWeb also did not respond to a request for comment.) And even if software programs can erase the satellites to salvage pixels that surround the bright streaks, data errors on the light-detecting chips will still pose a problem. "Operators of satellites in [low-Earth orbit] will present a significant threat to the main mission of LSST [Large Synoptic Survey Telescope]: discovery of the unexpected," the Rubin Observatory report concludes.

Astronomers and at least one private company are working on software that can eliminate some of the satellite streaks or change where the telescope is looking in order to avoid them. But it's hard to do because the satellites are moving and appear differently in various color filters, among other problems. Meredith Rawls of the University of Washington works on a team that will send out alerts for new phenomena Rubin Observatory catches in the night sky, which could reach 10 million alerts a night. Software is supposed to filter those and to automatically contact the global astronomy community only for meaningful events, such as asteroids or supernovae, she says.

"With the streaks, you can get these little weird blip-blip patterns, which our software will think is a potential object or a supernova, and it will flag it. And it's just a satellite," Rawls says. "This is going to [cause] more false positives than we would hope to have, and then you start trying to guess, how many? Is it going to be five a night or 500 a night? We don't know."

Rawls worked on a project that fed known satellite locations to the observatory's scheduler algorithm and found that if the telescope operators know where the satellites are, the algorithm can point the telescope elsewhere to avoid them. But this took so much effort that it risked choking the entire pipeline of observations, Rawls and her colleagues found. They're planning to submit their findings to the *Astrophysical Journal Letters*.

MEG SCHWAMB, AN ASTROPHYSICIST at Queen's University Belfast, was the astronomer who proposed doing the Rubin Observatory's twilight studies early in its 10-year lifetime, before satellite constellations made these observations impossible. Twilight is when near-Earth asteroids may be easily found and when the Rubin Observatory could detect many new ones. The Chelyabinsk meteor, for instance, which shocked everyone when it exploded over Russia in 2013, arrived from a similar direction as the sun and is just the kind of object the Rubin Observatory was designed to catch. But partially sunlit observations will be more difficult because the satellite constellations' solar panels will be illuminated at that time.

> "This is a deeper cultural question. Should Elon Musk control what people see in the night sky?"
> —Meg Schwamb *Queen's University Belfast*

"I never thought, as an astronomer, I would be advocating for doing things early because we don't know what the satellite field is going to be like," Schwamb says. More often astronomers anticipate extending their observatories' life spans and coming up with new campaigns in later years. Reversing this order, by instead making sure some basic science gets done before the observatory is blinded by light, is contrary to how many scientists plan their work and even their entire careers. Schwamb compares the satellite constellations to orbital advertisements and argues that humanity needs to figure out how to control them and what we want them to do. "If it wasn't Starlink but Coca-Cola, would we be okay with that?" she asks. "This is a deeper cultural question, too. Should Elon Musk control what people see in the night sky?"

Astronomers acknowledge that SpaceX has tried a variety of methods to darken its satellites, but the spacecraft are still visible, and other providers are not adopting any such mitigation strategies. What's more, newer Starlink satellites and those made by other companies are much larger and brighter. A company called AST SpaceMobile launched a prototype last September—BlueWalker 3. Two months later, when BlueWalker 3 deployed its 693-square-foot (64.4- square-meter) phased array of antennas to allow communication with cell phones on Earth, it became one of the brightest objects in the night sky, outshining more than 99 percent of the stars visible to the naked eye.

AST SpaceMobile aims to launch 168 even larger satellites, called BlueBirds, in the next few years. A company spokesperson said testing of BlueWalker 3 will help engineers evaluate the satellite's materials and judge its brightness, adding that the company is actively working with industry experts and NASA to mitigate brightness concerns. AST SpaceMobile is considering antireflective materials and changes to operations to make the satellites dimmer. There will be many fewer BlueBird satellites than other constellations, but they may pose a different type of problem. Some telescopes may be able to avoid very bright BlueBirds, the way some telescope cameras are designed to avoid bright objects such as the planets or the moon. But hundreds of them will be harder to escape. And a bright satellite passing through a digital camera's long exposure could fry the camera's sensitive electronics.

"It is clear that the technology is here. If you wanted to destroy the night sky, you can," McDowell says. "It's going to depend on the details of the business cases for these companies and the details of the regulatory environment whether or not that happens. Therefore, we should talk about whether that's acceptable."

But the pace of satellite construction and launches is much faster than the pace of astronomical research, let alone regulation. "Everyone is increasingly alarmed. We are not really sure where to put our shoulder to the wheel, because there are so many wheels," says Aparna Venkatesan, a cosmologist at the University of San Francisco who also studies cultural astronomy. "The power and the momentum are very one-sided. Astronomers tend to do things very slowly and carefully and convene conferences and meetings—and by then, another few thousand satellites have launched."

Several astronomers say new rules from the FCC would not be enough. Astronomers have been working with the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), which held a meeting on satellite swarms last spring, but the process is slow going. McDowell says if COPUOS considers protecting the night sky part of its mission, then member states may be encouraged to use their own national regulatory frameworks to make rules about how many bright satellites can be launched and where they can be.

Many astronomers hope their field may be saved if the satellite constellation operators eventually pull back because not enough people sign up for their Internet services. Or the companies may end up working together to slow their launches to prevent space debris, which would limit everyone's access to space. But the hard truth is that there isn't much anyone can do at this point to stop the steady launch of satellite

SPACECRAFT in a satellite constellation, as shown in this illustration, orbit in a collective pattern to work together.

Jacques Dayan/Alamy Stock Photo

constellations and their sun-reflecting solar panels.

Astronomers have even resorted to a sort of gallows humor about the coming years. Several people pointed out a satellite loss from last February, when some Starlink satellites were in a low orbit in preparation to move to their permanent altitudes. A solar flare traveled to Earth and sparked a plasma storm in the uppermost layers of the atmosphere, causing excess atmospheric drag and radio interference; 40 satellites tumbled back down and burned up. Asked what astronomers can do to prepare for the growing flotilla of satellites, more than one joked, "Wait for solar maximum," when the sun's activity is expected to increase and cause more such storms.

Short of software patches or a geomagnetic storm that knocks out the satellites, physical changes to the spacecraft are one way to prevent total viewfinder contamination. Dimmer objects are easier for software to edit out, and lower orbital altitudes would require faster speeds so the satellites don't fall to Earth, which means they would zip out of the way more quickly. Rubin Observatory team members are hoping private companies will build less reflective satellites and park them in lower orbits, but these decisions would be up to the companies; there are no laws requiring them to do so. The companies should reach out to astronomers and explain their projects' goals and potential impacts on astronomy, Rawls says. "Kind of like in a city, when they want to build a new bike lane, it takes three years because they have to have 700 meetings with stakeholders. I would like to have that for space," she adds. "But in some ways, everyone who ever looks up is a stakeholder in this. And that makes it a real challenge."

Astronomers are not monolithic in their opinions about the issue, and members of the community have expressed varying levels of awareness and alarm about satellite constellations. The amount of fear depends in part on one's knowledge of the satellites and on one's specific interest, including which observatories are affected, McDowell says. "If your science is like the Rubin Observatory, then yes, the sky is probably falling. If your science is narrow-field spectroscopy [studying starlight], it's not as obvious that the sky is falling—but it yet may be," he says.

The alarm is focused on the near future, and although many people are worried, no one knows how bad it will be—or how long the problem will last. It may simply represent a preview of what's to come for the cosmos in general. Cosmologists such as Tyson debate the eventual fate of the universe. One likely scenario is a "big freeze," in which all matter is pushed so far apart that stars will burn out and go extinct. As the universe continually expands, accelerated by the mysterious force called dark energy, the broader cosmos will eventually become invisible from Earth. If any humans remain by that time, they will have to dispense with the starry heavens as a means of understanding the universe—and themselves.

"This is a version of that," Tyson says of the satellite constellations. "Very soon the sky will be visually dominated by these satellites rather than the stars themselves, and that will be true independent of whether you live in a city or out in the country. The future is one in which the sky is twinkling constantly, everywhere, from all of these satellites." SA

FROM OUR ARCHIVES

Orbital Aggression. Ann Finkbeiner; November 2020.

scientificamerican.com/magazine/sa

CLIMATE

CONCRETE CURE

New techniques can greatly reduce the enormous carbon emissions from cement and concrete production

CONCRETE IS EVERYWHERE: IN BUILDINGS, ROADS, SIDEWALKS, BRIDGES and foundations for almost every structure imaginable. We make more concrete than we do any other material on Earth, and that volume is rising because of global development, especially in China and India. Cement—the powdery binder that holds the sand or crushed stone in concrete together—is one of the most energy-intensive products on the planet. Limestone used in it is baked at up to 1,450 degrees Celsius (2,640 degrees Fahrenheit) in enormous kilns that are fired almost exclusively with fossil fuels. The chemical reactions involved produce even more carbon dioxide as a by-product. Making one kilogram of cement sends one kilogram of CO_2 into the atmosphere. Worldwide every year cement and concrete production generates as much as 9 percent of all human CO_2 emissions.

Societies have made cement and concrete in pretty much the same way for a century. Trials have shown that a portion of the cement in a mix can be replaced with calcined (burnt) clay or ingredients made from wastes such as fly ash and slag without a loss of strength but with fewer emissions. There is not enough supply to meet demand, but such alternatives can reduce CO_2 to an extent.

Other alternative materials and processes can cut emissions significantly. Some are already spreading; others are experimental. Because most cement and concrete is made locally or regionally, close to where it is used, the availability of substitute materials, revised building standards to allow their use, capital costs for retooling and market acceptance are all practical challenges.

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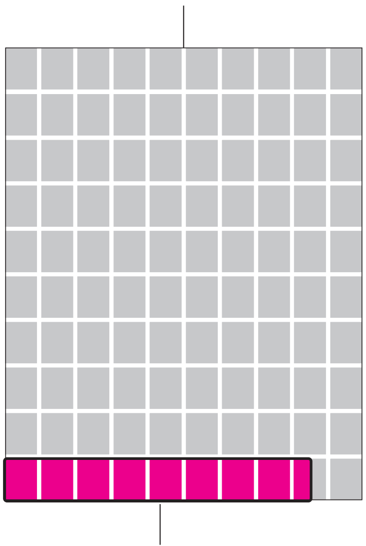
Worldwide CO_2 Emissions, 2014



Cement and concrete production generated 2.5 billion metric tons of CO_2 emissions in 2014—**8 to 9 percent of global human emissions.** Demand for cement and concrete is predicted to grow 12 to 23 percent above 2014 levels by 2050. Some 4.3 billion metric tons of cement were made in 2021.

FROM OUR ARCHIVES

Ships of Stone. R. G. Skerett; November 17, 1917.

scientificamerican.com/magazine/sa

BETTER CEMENT PRODUCTION

Cement manufacturing consumes large amounts of energy, much of it from fossil fuels that emit CO_2. Certain steps also emit CO_2 directly, notably, the creation of lime (*step 3*) and then clinker, a hardening agent (*step 4*). Replacing fossil fuels with renewable energy sources and raising efficiency across production could reduce the carbon footprint by up to 40 percent. Using different raw materials for clinker could dramatically lower the remaining 60 percent of carbon emissions.

1. Mine and Grind Limestone

HOW IT WORKS

Deposits containing calcium carbonate, such as limestone or chalk, are mined from quarries, which may include small amounts of clay containing silicon, aluminum or iron. The ingredients are crushed into pieces less than 10 centimeters in size and then milled into a powder called raw meal.

ROOM TO IMPROVE

Start with basalt instead of limestone or use “carbon-negative limestone” produced with waste CO_2 (*step 2*), reducing emissions by up to 60 to 70 percent.

The process shown is for so-called dry kilns; they have widely replaced wet kilns, which use even more energy.

2. Preheat Raw Meal …

HOW IT WORKS

Raw meal in a chamber above a kiln is heated to temperatures as high as 700 degrees C by the kiln’s hot, swirling exhaust gases, driving off moisture.

ROOM TO IMPROVE

Burn oxygen-rich air to lessen CO_2 emissions. Add equipment to capture CO_2, which could reduce emissions by up to 60 percent. Use the waste CO_2 to make carbon-negative limestone (*step 1*). Burn biomass or waste to heat the kiln instead of fossil fuel.

3. … and Convert Meal into Lime

HOW IT WORKS

Preheated meal is burned in a combustion chamber immediately above and inside the top of the kiln at 750 to 900 degrees C, converting calcium carbonate to calcium oxide (quicklime) and CO_2. This step accounts for 60 to 70 percent of the CO_2 driven out of the raw materials and consumes about 65 percent of all fuel used in the entire cement production process.

ROOM TO IMPROVE

Burn oxygen-rich air to lessen CO_2 emissions. Add equipment to capture CO_2. Use an electric kiln run on renewable energy, reducing emissions for steps 2, 3 and 4 by 30 to 40 percent.

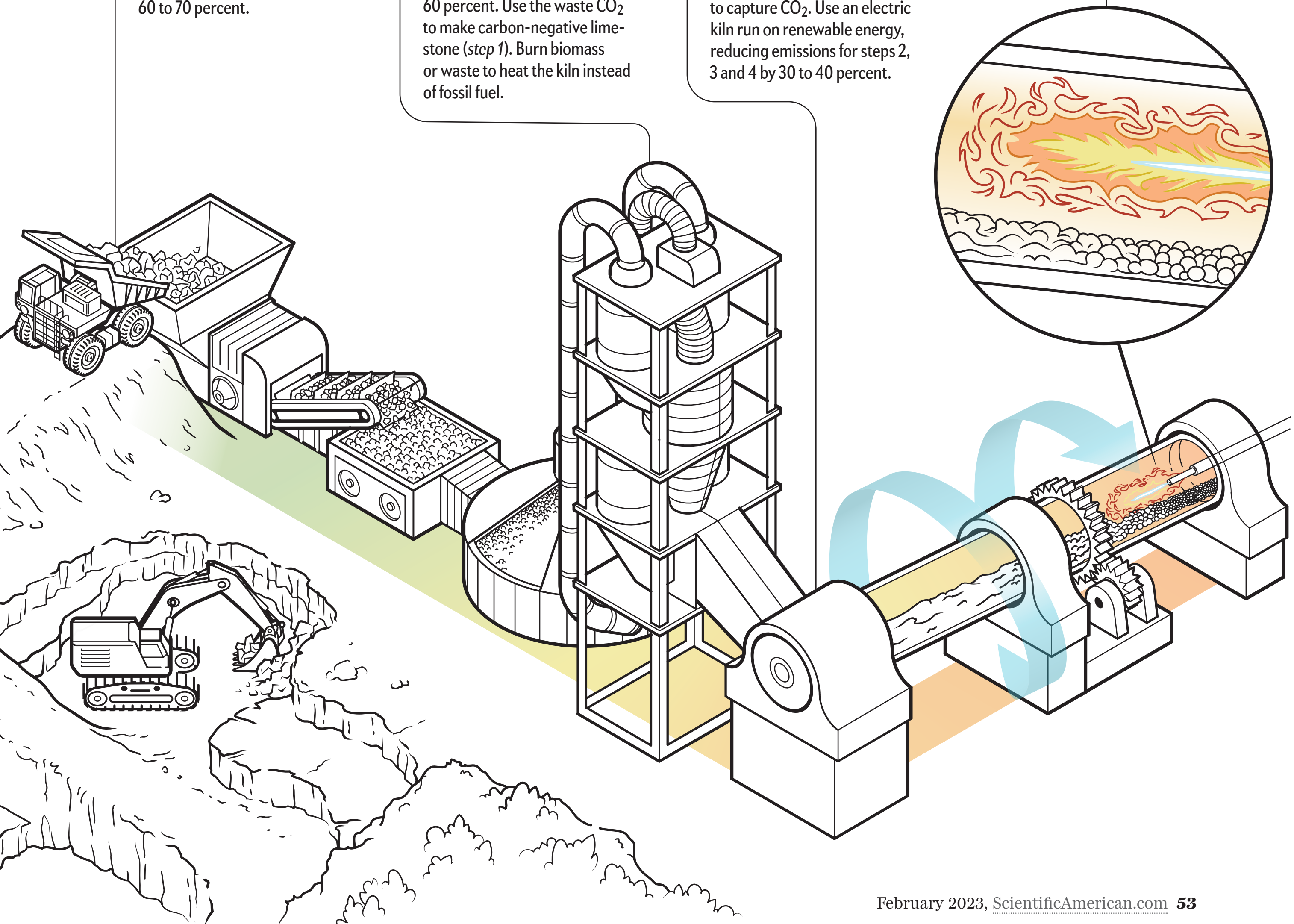
4. Convert Lime into Clinker

HOW IT WORKS

Lime is burned at up to 1,450 degrees C in a kiln rotating three to five times per minute. This process melts and sinters (fuses) the lime into Portland cement clinker—dark gray nodules three to 25 millimeters in diameter—and drives off more CO_2. Clinker is the binder that causes cement to harden when it reacts with water.

ROOM TO IMPROVE

Add a mineralizer such as calcium fluoride or sulfate to lower the lime’s melting temperature, saving energy.



5. Cool and Store Clinker

HOW IT WORKS
Hot clinker is run across grates where air blowers cool it to about 100 degrees C. Once cool, it is stored in a silo and can last a long time without degrading, so it may be sold as its own commodity.

ROOM TO IMPROVE
Electrify the process or pipe in waste heat from step 3 for initial cooling.

6. Blend Clinker with Gypsum

HOW IT WORKS
Clinker is mixed with gypsum at a ratio of 20 or 25 to one.

ROOM TO IMPROVE
Electrify the process.

7. Grind the Blend into Portland Cement

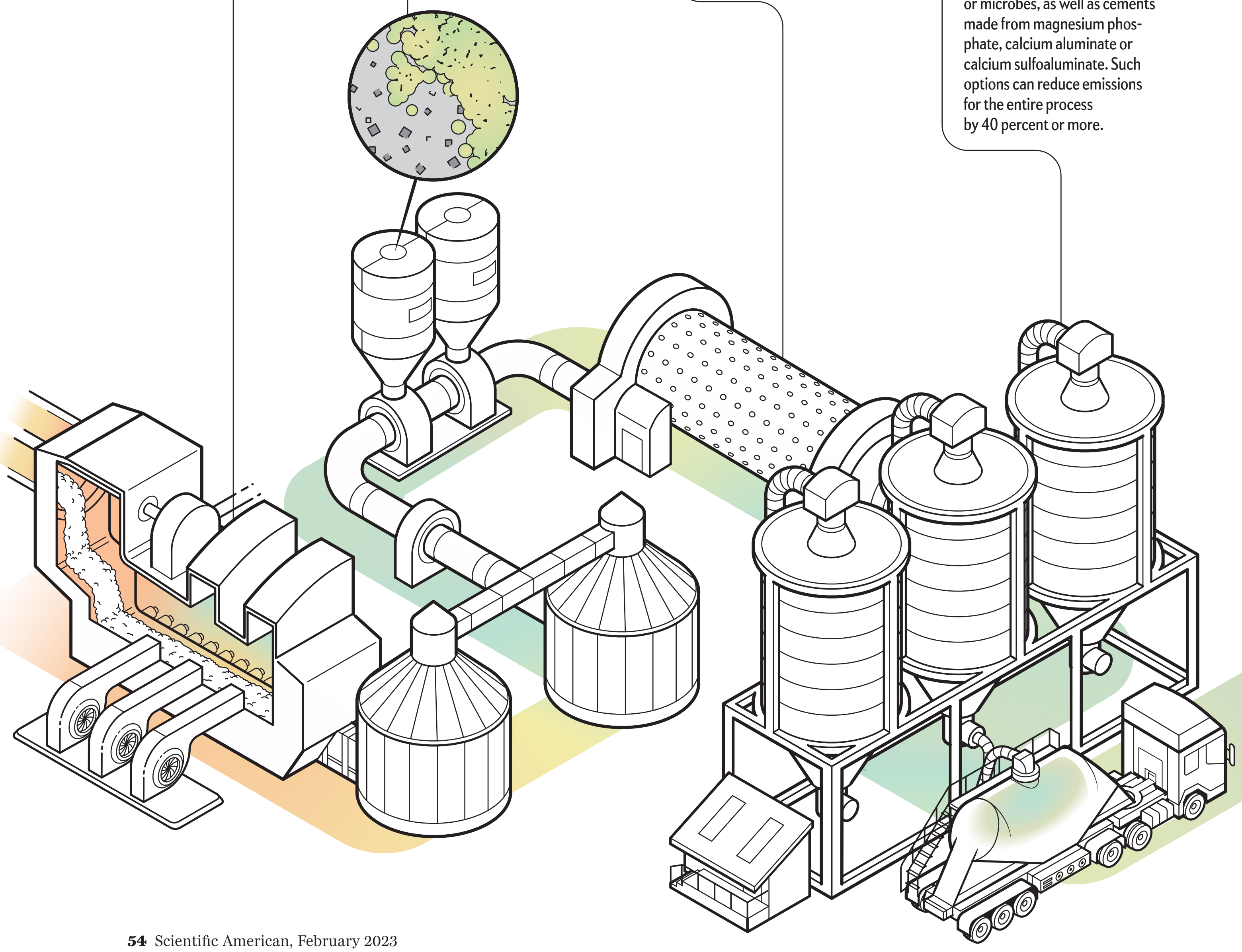
HOW IT WORKS
Roller mills or ball mills grind the clinker and gypsum into a fine gray powder known as Portland cement.

ROOM TO IMPROVE
Add finely ground limestone to replace up to 35 percent of the cement, reducing emissions created during earlier production steps. This mix is known as Portland-limestone cement. Create “blended cements” by adding fly ash (20 to 40 percent), slag (30 to 60 percent) or calcined clay (20 to 30 percent) to lower the clinker-to-cement ratio, reducing emissions by similar percentages.

8. House Cement in Silos

HOW IT WORKS
The powder is thoroughly mixed so it is uniform throughout and is then stored in a silo. It will be packed into bags for retail sale or loaded into trucks headed for concrete mix facilities.

ROOM TO IMPROVE
Consider lower-carbon alternatives to Portland cement for certain applications. These alternatives include alkali-activated cements and bio-cements generated by algae or microbes, as well as cements made from magnesium phosphate, calcium aluminate or calcium sulfoaluminate. Such options can reduce emissions for the entire process by 40 percent or more.



BETTER CONCRETE PRODUCTION

Concrete is usually made at or near a construction site. Optimizing structural designs can reduce the amount of concrete needed (*step 3*). Reusing and processing concrete after demolition (*step 4*) can absorb CO_2 from the atmosphere, offsetting some emissions from the original cement production.

1. Mix Cement, Water and Aggregate

HOW IT WORKS

Cement is mixed with specific amounts of water and aggregate such as sand, gravel or crushed stone at ambient temperature until a desired fluidic consistency is reached. About 80 percent of the mix is aggregate.

ROOM TO IMPROVE

Change conveyors and mixers to run on renewable electricity, greatly reducing emissions. Include an additive such as biochar or algae to increase the concrete's strength or tailor its workability or setting time, reducing emissions by 1 to 5 percent or more.

2. Transport to Job Site

HOW IT WORKS

Concrete is mixed inside a drum-mixer truck that transports it to a construction site.

ROOM TO IMPROVE

Switch to electric trucks. Minimize, collect and upcycle waste concrete into other precast materials such as highway barriers.

3. Build a Structure

HOW IT WORKS

Building design dictates the shape, volume and strength of concrete elements needed.

ROOM TO IMPROVE

Optimize structural designs so concrete is not wasted. Switch specifications from requiring minimum amounts of cement in the concrete to requiring a given compressive strength, which can reduce the necessary cement content. Change building codes to allow for new, alternative and blended cements. Rely on concrete's ability to gain strength over time by specifying compressive strengths at two or three months instead of the common one month, which can lessen the amount of material needed.

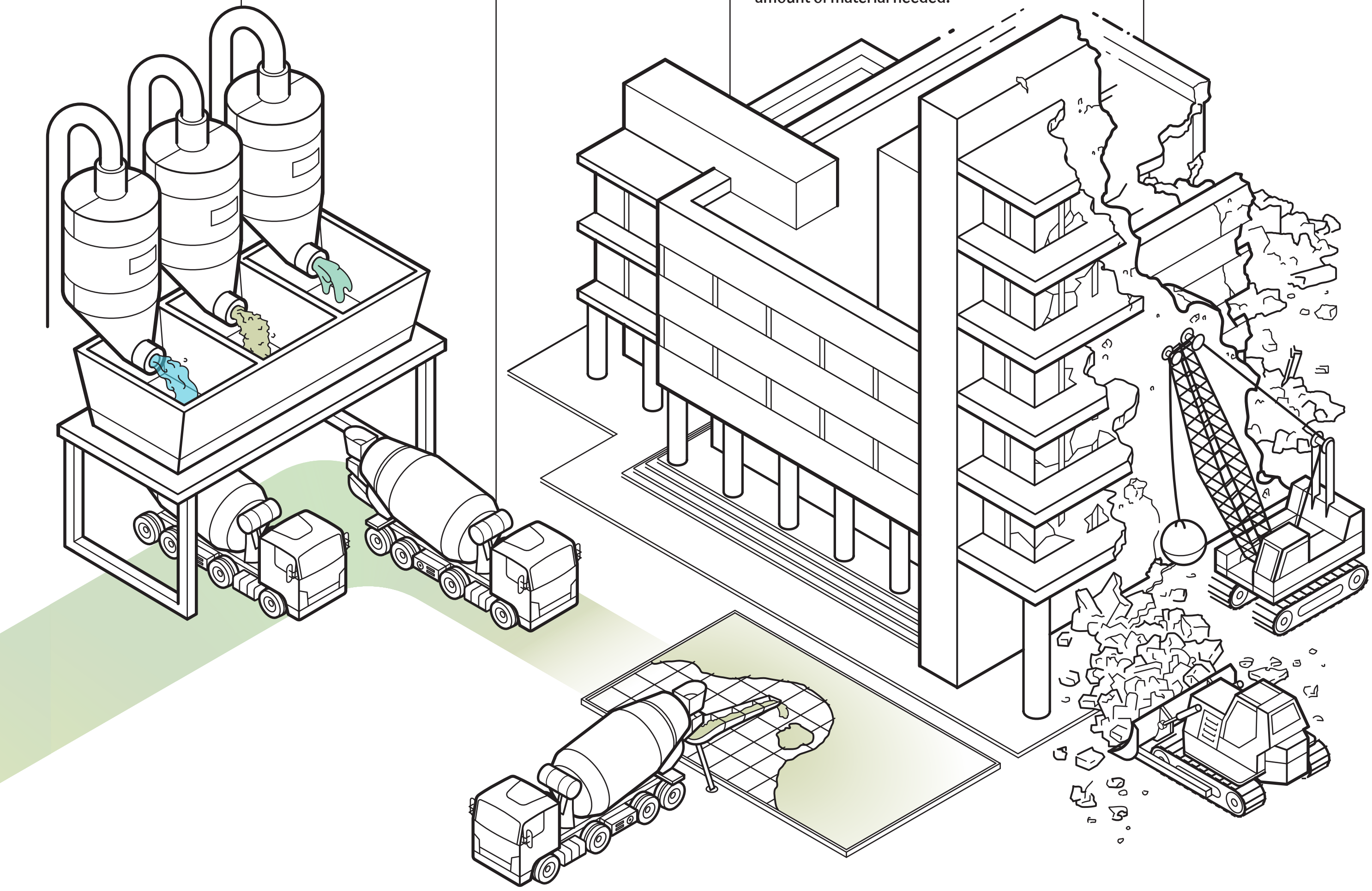
4. Plan End of Life

HOW IT WORKS

Demolished concrete is often dumped into landfills or crushed and used as a base material for roads and highways.

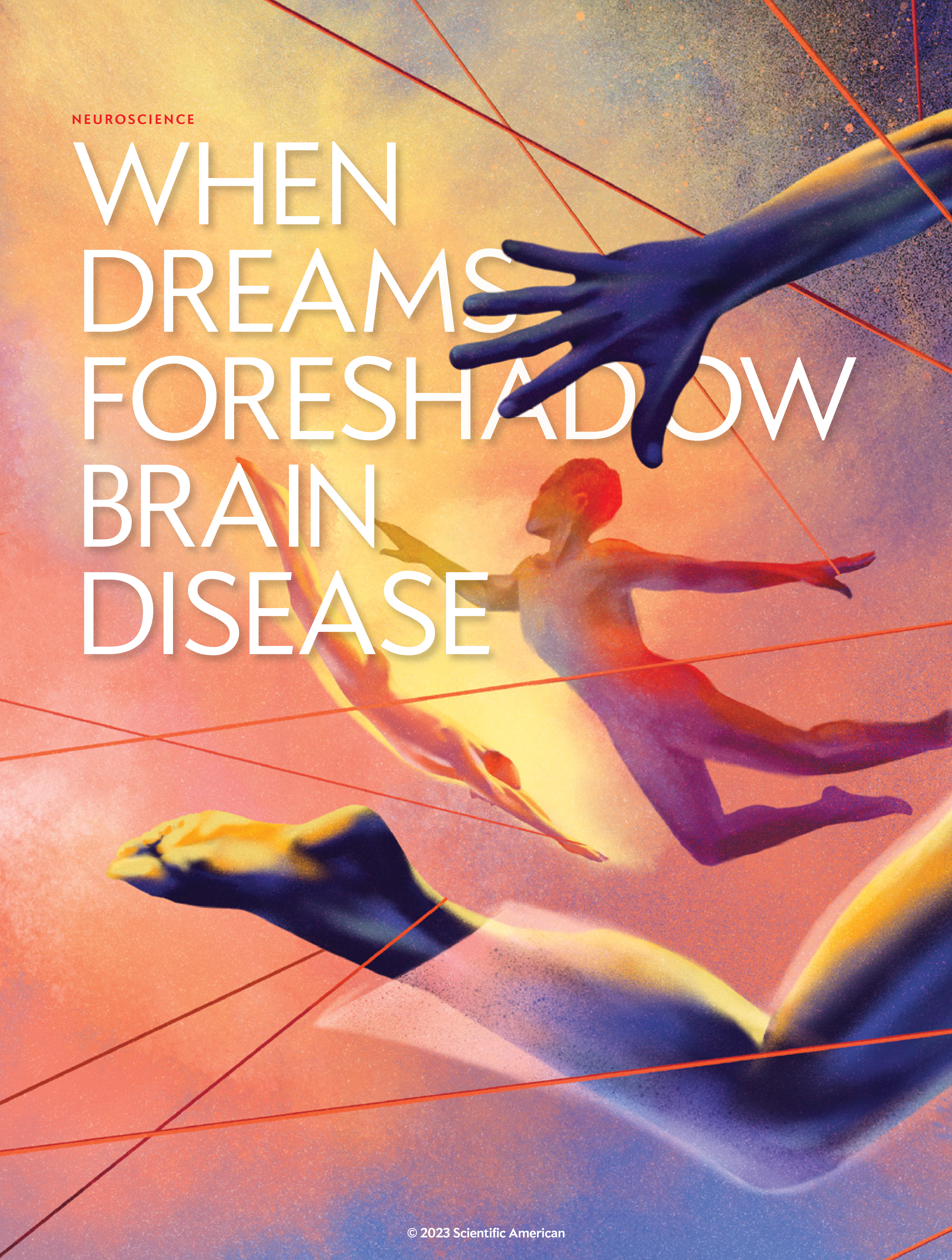
ROOM TO IMPROVE

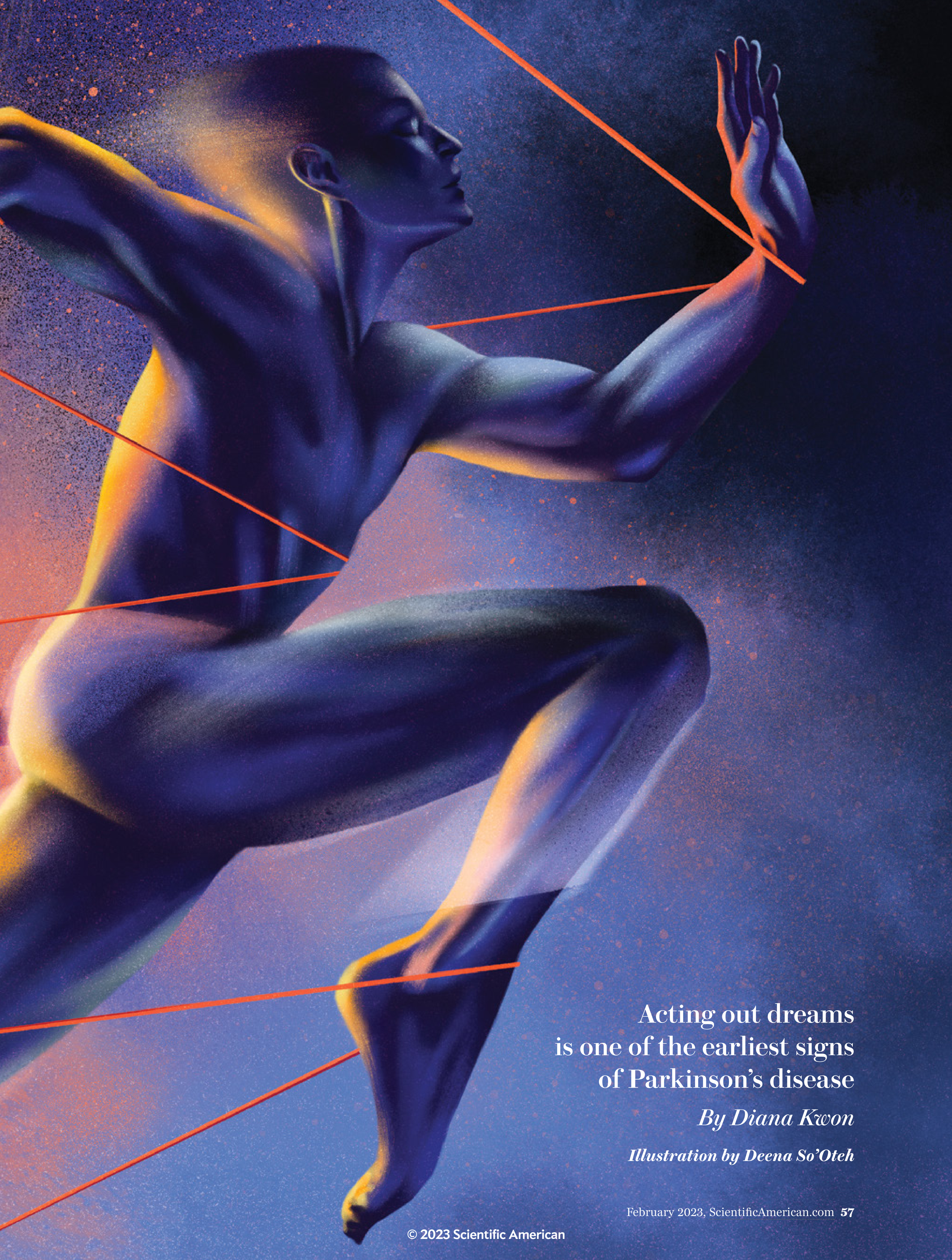
Design for deconstruction so concrete's elements can be reused in whole or in part. If concrete is demolished, grind it and spread it thinly to maximize its surface area and expose it to air for as long as possible to absorb CO_2. With years of exposure, concrete can absorb perhaps as much as 17 percent of the CO_2 emitted when the cement for that concrete was manufactured.



NEUROSCIENCE

WHEN DREAMS FORESHADOW BRAIN DISEASE





Acting out dreams is one of the earliest signs of Parkinson's disease

By Diana Kwon

Illustration by Deena So'Oteh

Diana Kwon is a freelance journalist who covers health and the life sciences. She is based in Berlin.

ALAN ALDA WAS RUNNING FOR HIS LIFE. THE ACTOR, BEST KNOWN FOR his role on the television series *M*A*S*H,* wasn't on a set. This threat was real—or at least it felt that way. So when he saw a bag of potatoes in front of him, he grabbed it and threw it at his attacker. Suddenly, the scene shifted. He was in his bedroom, having lurched out of sleep, and the sack of potatoes was a pillow he'd just chucked at his wife.

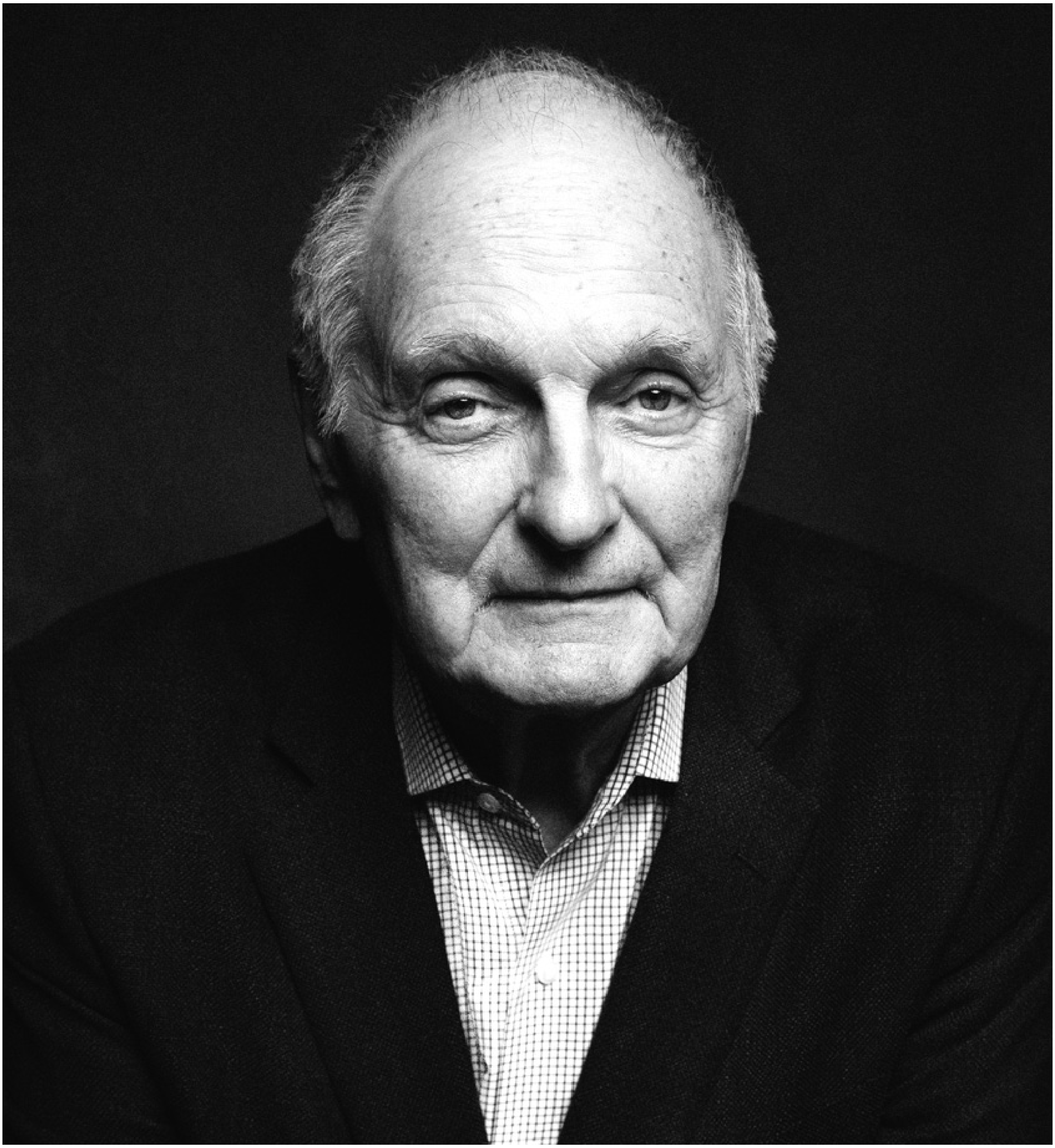
Acting out dreams marks a disorder that occurs during the rapid eye movement (REM) phase of sleep. Called RBD, for REM sleep behavior disorder, it affects an estimated 0.5 to 1.25 percent of the general population and is more commonly reported in older adults, particularly men. Apart from being hazardous to dreamers and their partners, RBD may foreshadow neurodegenerative disease, primarily synucleinopathies—conditions in which the protein α-synuclein (or alpha-synuclein) forms toxic clumps in the brain.

Not all nocturnal behaviors are RBD. Sleepwalking and sleep talking, which occur more often during childhood and adolescence, take place during non-REM sleep. This difference is clearly distinguishable in a sleep laboratory, where clinicians can monitor stages of sleep to see when a person moves. Nor is RBD always associated with a synucleinopathy: it can also be triggered by certain drugs such as antidepressants or caused by other underlying conditions such as narcolepsy or a brain stem tumor.

When RBD occurs in the absence of these alternative explanations, the chance of future disease is high. Some epidemiological studies suggest that enacted dreaming predicts a more than 80 percent chance of developing a neurodegenerative disease within the patient's lifetime. It may also be the first sign of neurodegenerative disease, which on average shows up within 10 to 15 years after onset of the dream disorder.

One of the most common RBD-linked ailments is Parkinson's disease, characterized mainly by progressive loss of motor control. Another is Lewy body dementia, in which small clusters of α-synuclein called Lewy bodies build up in the brain, disrupting movement and cognition. A third type of synucleinopathy, multiple system atrophy, interferes with both movement and involuntary functions such as digestion. RBD is one of the strongest harbingers of future synucleinopathy, more predictive than other early markers such as chronic constipation and a diminished sense of smell.

Descriptions of dream enactment by people with Parkinson's are as old as recognition of the disease itself. In James Parkinson's original description, "An Essay on the Shaking Palsy," published in 1817, he wrote: "Tremulous motions of the limbs occur during sleep, and augment until they awaken the patient, and frequently with much agitation and alarm." But despite similar reports over the next two centuries, the connection between dreams and disease remained obscure—so much so that Alda had to convince his neurologist to do a brain scan for Parkin-



ACTOR ALAN ALDA helps to raise awareness of Parkinson's and its early symptoms to give people a head start on dealing with the disease.

Jesse Dittmar/Redux

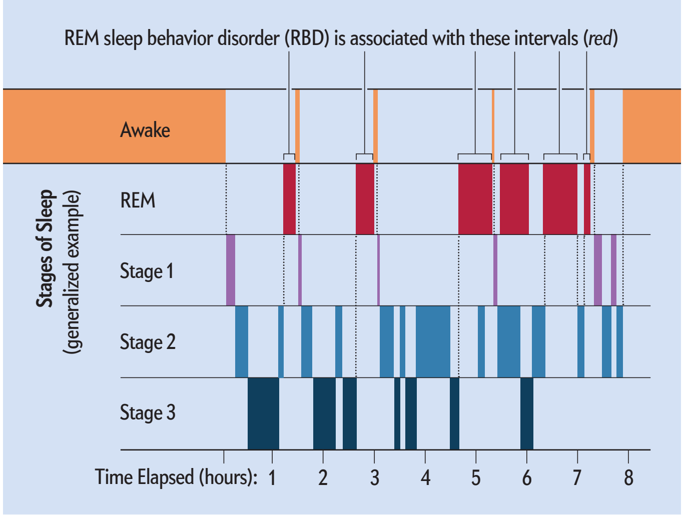
son's after he read about the link in a 2015 news article.

Those scans confirmed Alda's suspicion: he had Parkinson's. He shared his experience with the public "because I thought anybody who has any symptom, even if it's not one of the usual ones, could get a head start on dealing with the progressive nature of the disease," he says. "The sooner you attack it, I think, the better chance you have to hold off the symptoms."

In recent years awareness of RBD and an understanding of how it relates to synucleinopathies have grown. Studying this link is giving researchers ideas for early intervention. These advances contribute to a growing appreciation of the so-called prodromal phase of Parkinson's and other neurodegenerative disorders—when preliminary signs appear, but a definitive diagnosis has not yet been made. Among the early clues for Parkinson's, "RBD is special," says Daniella Berg, a neurologist at the University Hospital Schleswig-Holstein in Germany. "It's the strongest clinical prodromal marker we have."

Dream Cycles

When we fall asleep, the brain begins to cycle through different stages, marked by characteristic patterns of activity. Brain waves during rapid eye movement (REM) sleep look rather like those in awake brains, representing vivid dreams. Muscles are normally immobilized to prevent injury from acting dreams out. But in RBD, or REM sleep behavior disorder, this sleep-time paralysis is lifted, likely by damage to the brain stem.



Source: "Across the Consciousness Continuum—From Unresponsive Wakefulness to Sleep," by Christine Blume et al., in *Frontiers in Human Neuroscience*, Vol. 9; March 2015 (*reference*)

LIFTING THE BRAKE

RAY MERRELL, a 66-year-old living in New Jersey, started acting out his dreams around 15 years ago. His dreamscapes became action-packed, like "something you'd watch on TV," Merrell says. He often found himself either being chased by or chasing a person, animal or something else. In the real world, Merrell was flailing, kicking and jumping out of bed. Some of his violent nighttime behaviors injured him or his wife.

In people with RBD, the brakes that normally immobilize them during REM sleep—the stage of sleep most closely linked with dreaming—are lifted. (Dreaming also occurs in non-REM sleep, but dreams during REM are longer, more vivid and more bizarre.)

In the 1950s and 1960s French neuroscientist Michel Jouvet conducted a series of experiments that revealed just how chaotic unrestricted movements during REM sleep could be. By lesioning parts of the brain stem in cats, Jouvet inhibited the muscle paralysis that occurs in many species during REM sleep. Cats that had gone through the procedure acted normally when awake, but when asleep they became unusually active, exhibiting intermittent bursts of activity such as prowling, swatting, biting, playing and grooming. Despite this remarkably awakelike behavior, the cats remained fast asleep. Jouvet observed that the cats' sleeping actions often were unlike their waking habits. Felines that were "always very friendly when awake," he wrote, behaved aggressively during REM sleep.

In the late 1980s Carlos Schenck, a psychiatrist at the University of Minnesota, and his colleagues published the first case reports of RBD. Patients described having violent dreams and aggressive sleep behaviors that contrasted sharply with their nonviolent nature while awake—echoing Jouvet's documentation of otherwise friendly felines that turned belligerent during sleep. One patient, for example, said he had a dream about a motorcyclist trying to ram him on the highway. He turned to kick the bike away—and woke to his wife saying, "What in heavens are you doing to me?" because he was "kicking the hell out of her." Another said he dreamed of breaking a deer's neck and woke up with his arms wrapped around his spouse's head.

To test whether these bizarre behaviors may reflect damage to the brain stem, as in Jouvet's cats, Schenck and his colleagues kept track of such patients to see whether they might develop a brain disease. In 1996 they reported that in a group of 29 RBD patients, all of whom were male and age 50 or older, 11 had developed neurodegenerative disease an average of 13 years after the onset of their RBD. By 2013, 21 of them, or more than 80 percent, had developed a neurodegenerative condition—the most common of which was Parkinson's.

Subsequent studies confirmed this link. Of 1,280 patients across 24 centers around the world, 74 percent of people with RBD were diagnosed with a neurodegenerative disease within 12 years. Sometimes RBD shows up decades before other neurological symptoms, although the average lag appears to be about 10 years. When dream enactment occurs alongside other early signs of synucleinopathies, people tend to develop a neurodegenerative disease more rapidly.

Many researchers expressed skepticism about this link early on, says Bradley Boeve, a professor of neurology at the Mayo Clinic in Rochester, Minn. "We would get reviewer comments back saying that this is hogwash," he says. But the connection between RBD and synucleinopathy has become well accepted: "I think that's pretty much gospel now."

Some scientists suspect RBD results from an aggregation of synuclein and associated neurodegeneration in areas of the brain stem that immobilize us during REM sleep. In its normal, benign, form, the protein is involved in the functioning of neurons, but when "misfolded" into an atypical configuration, it can form toxic clumps. Autopsies have shown that more than 90 percent of people with RBD die with signs of synuclein buildup in their brains. There are no established methods to probe for synuclein clusters in the brains of living patients, but scientists have looked for the toxin in other parts of the body. Alejandro Iranzo, a neurologist at the Hospital Clinic Barcelona in Spain, and his colleagues were able to detect misfolded synuclein in the cerebrospinal fluid of 90 percent of patients with RBD.

As an early manifestation of Parkinson's and related diseases, RBD can help scientists trace the ways

Graphic by Jen Christiansen

in which toxic synuclein spreads throughout the body and brain. Evidence is mounting that at least in some patients, pathology may begin in the gut and spread up through lower brain structures such as the brain stem to the higher regions influencing movement and cognition. One likely pathway is the vagus nerve, a bundle of nerve fibers connecting all the major organs with the brain. Alpha-synuclein clumps injected into the guts of mice can spread to the brain via the vagus—and in humans, at least one epidemiological study has shown that cutting the vagus, a procedure sometimes used to treat chronic stomach ulcers, decreases the risk for Parkinson's later in life.

Some researchers hold that Parkinson's has two subtypes: gut first and brain first. RBD is highly predictive of later Parkinson's, says Per Borghammer, a professor of clinical medicine at Aarhus University in Denmark, but the converse is not true: only about a third of people with Parkinson's get RBD before developing motor symptoms. People with RBD have gut-first Parkinson's, Borghammer posits, and generally experience symptoms such as constipation long before motor and cognitive decline. But in the two thirds of patients who are brain first, RBD may emerge later than problems with movement—or never appear.

THE DREAM THEATER

DOES DAMAGE to the brain stem also affect the content of dreams and the actions of dreamers? Sleep researcher Isabelle Arnulf, a professor of neurology at Sorbonne University in Paris, developed a keen interest in the dream-time behaviors of her Parkinson's patients after noticing an unusual pattern: although these people struggled with movement while awake, their spouses often reported that they had no trouble moving while asleep. One particularly memorable patient, according to Arnulf, had been dreaming of crocodiles in the sleep lab when he lifted a heavy bedside table above his head and loudly shouted, "Crocodile! Crocodile!" to an empty room. When awake, he struggled to lift objects and to speak.

Intrigued by such observations, Arnulf and her colleagues began compiling the behaviors people exhibited during REM sleep. This collection, which has grown over the past decade and a half to include hundreds of hours of footage of dream-enacting sleepers and hundreds of dream reports, has enabled Arnulf to uncover unexpected features of RBD dreams and insights into some fundamental questions about how—and why—we dream.

Merrell, Alda and many other people with RBD often have dreams in which they face danger. In one study led by Arnulf, researchers found that among people with RBD, 60 percent reported dreams involving some kind of threat, and 75 percent confronted their attacker instead of running away. People who report more frequent distressing dreams are also at greater risk of developing Parkinson's. "It's textbook for people with RBD to have violent dreams where they are on the defensive," says Yo-El Ju, a professor of neurology at Washington University in St. Louis. But whether this is attributable to recall bias—people tending to remember more violent dreams because they are more memorable—remains an open question, she adds.

Arnulf's group also found that a significant proportion of RBD dreams are nonviolent. In one study, 18 percent of patients flew, sang, danced, laughed, lectured or enacted other peaceable activities. In another study with 52 RBD patients, the researchers looked at subtle changes in facial expressions during sleep. Half the people smiled and a third laughed during mainly REM sleep, suggesting that RBD dreams may be more positive than previously described. Arnulf hypothesizes that violent dreams may be reported more often because aggressive behaviors are more likely to wake up the dreamer or their spouse. "I'm pretty convinced that in RBD patients, it's just that the window is open on dreaming, but their dreams are not different from ours," Arnulf says.

In people with the dream behavior disorder called RBD, the brakes that normally immobilize them during REM sleep are lifted.

The finding that RBD patients display a range of emotions while dreaming led Arnulf to believe that what researchers learn about their dreams may apply to the broader population. Her team discovered, for example, that a small percentage of people with RBD were never able to recall their dreams despite acting out dreamlike behaviors while asleep—suggesting that self-described nondreamers may, in fact, dream.

One mystery of RBD is whether people are acting out their dreams or whether their movements are modifying their dream narratives, says Birgit Högl, a professor of neurology and sleep medicine at the Medical University of Innsbruck in Austria. As for the question that originally intrigued Arnulf—why the impaired movement characteristic of Parkinson's seems to disappear during sleep in some patients—work by other groups has helped suggest an answer. Neurologist and psychiatrist Geert Mayer, formerly at Hephata Clinic in Germany, and his colleagues revealed in a 2015 study that the basal ganglia, movement-related structures near the base of the brain where neurodegeneration occurs in people with Parkinson's, were silent during dream enactments in RBD patients. But other brain regions involved in producing movement, such as the motor cortex, were active.

Findings such as these suggest that in people with RBD, movement is generated through a motor circuit that bypasses the basal ganglia. "This sort of shows

Where Does Parkinson's Begin?

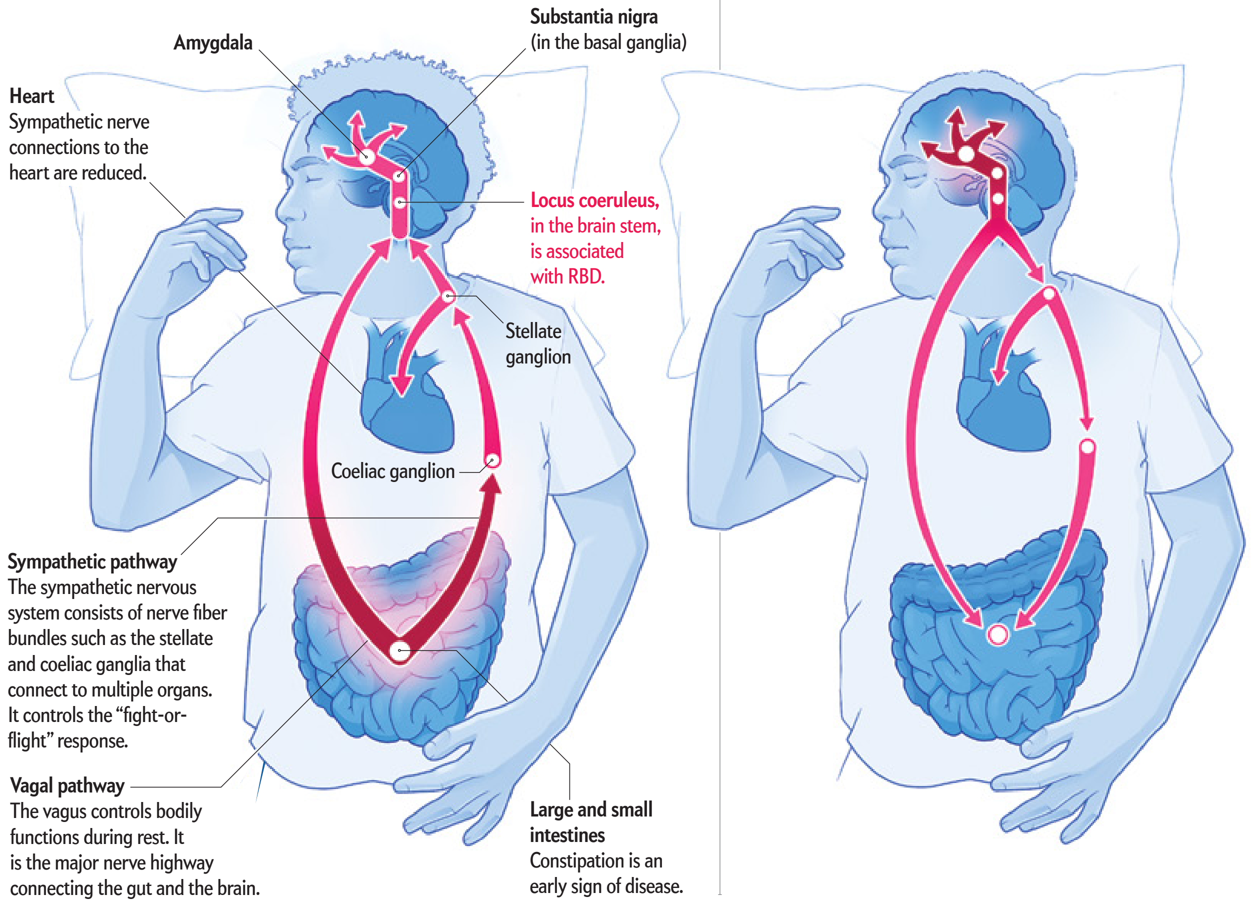
For decades neurologists saw Parkinson's primarily as a disease caused by the progressive loss of neurons in the substantia nigra, a brain region involved in movement. In the early 2000s neuroanatomist Heiko Braak of the University of Ulm in Germany and his colleagues proposed that the ailment may begin in the gastrointestinal tract, an idea that has gained support in recent years. Some researchers hold that Parkinson's has two subtypes, one originating in the gut (*left*) and the other in the brain (*right*). In this view, enacted dreaming precedes Parkinson's when the disease travels from the gut to the brain.

In the Gut

This model posits that toxic clumps of a protein called alpha-synuclein begin aggregating in the gut, then travel through the highways of nerve fibers that help to control heart rate, digestion, and other bodily functions. Eventually they spread to the brain stem, leading to RBD, and years later reach higher brain regions, affecting movement, cognition and other processes.

In the Brain

In this model, alpha-synuclein builds up in the amygdala, substantia nigra and other parts of the brain, affecting emotion, movement and cognition, and then descends through the brain stem. So RBD develops after the onset of more characteristic symptoms of Parkinson's.



Heart
Sympathetic nerve connections to the heart are reduced.

Sympathetic pathway
The sympathetic nervous system consists of nerve fiber bundles such as the stellate and coeliac ganglia that connect to multiple organs. It controls the "fight-or-flight" response.

Vagal pathway
The vagus controls bodily functions during rest. It is the major nerve highway connecting the gut and the brain.

Large and small intestines
Constipation is an early sign of disease.

Source: "Prodromal Parkinson Disease Subtypes—Key to Understanding Heterogeneity," by Daniela Berg et al., in *Nature Reviews Neurology*, Vol. 17; April 2021 (*reference*)

Graphic by Now Medical Studios

that whatever's going on in Parkinson's disease in terms of your movement doesn't apply to you when you're asleep," says Ronald Postuma, a professor of neurology at McGill University. It also raises a tantalizing possibility for therapy: "What if you could mimic whatever that motor state is when a person is asleep but keep them otherwise awake?"

EARLY INTERVENTION

MERRELL HAD BEEN enacting dreams for several years before he realized it might be a sign of a bigger problem. It began during a rough patch at work, and he had dismissed the occasional sleep outbursts as deriving from job-related stress. One evening, mid-dream, Merrell threw himself into a corner of a nightstand, breaking his skin but narrowly missing his breastbone. The close call with a very serious injury "really got me thinking that I better look into this," Merrell says.

When Merrell was diagnosed with RBD in 2011, his doctor briefly mentioned the risk of developing other conditions down the line but "didn't give me assurances or any other advice," Merrell recalls. But when he began researching the condition online, he discovered many studies on RBD patients who developed a neurodegenerative disease in later life. “The more I searched,” he adds, “the more I realized, wow, this has some pretty significant implications.”

The available treatments for Parkinson’s and other synucleinopathies can currently only manage symptoms. They’re unable to slow or stop the underlying neurodegeneration. “The worst news I have to give as a sleep doctor is to tell someone that they have RBD,” Ju says.

But several new therapeutics for Parkinson’s and other synucleinopathies are being developed, and many neurologists believe early intervention could be crucial. “The Parkinson’s disease field, in particular, is full of failed treatment trials,” Ju says. “By the time people have the disease, it’s probably too late to intervene—too many cells have died.” Going back and testing these seemingly failed medications in RBD patients may prove more successful, she adds, because as a much earlier stage of disease, RBD provides a window where treatments are more likely to be effective. “A lot of people are viewing RBD as similar to high cholesterol,” Boeve says. “If you have high lipid levels, they increase your risk for heart disease and stroke. If you can alter that pathophysiological process, you can reduce the risk or delay the onset.”

Ju, Postuma and Boeve are co-leaders of the North American Prodromal Synucleinopathy (NAPS) Consortium, which launched in 2018. The NAPS investigators aim to pinpoint clinical and biological markers through various means, including brain scans, genetic screens, and tests of blood and cerebrospinal fluid. The researchers hope these markers will eventually indicate how and when a person with RBD will develop a neurodegenerative disease later in life—and which disease they will end up with. Ideally, such biomarkers would help scientists identify RBD patients for investigative therapies that target α-synuclein years before debilitating symptoms appear. The ultimate goal of NAPS, Ju says, “is essentially to prepare for clinical trials for protective treatments.”

In 2021 NAPS received a $35-million grant from the National Institutes of Health for this work, which will be carried out across eight sites in the U.S. and one in Canada. In a parallel effort, Högl, along with other researchers in Europe, is gathering a similar cohort of patients from multiple institutions across the continent for future clinical studies. Wolfgang Oertel, a neurologist at Philipps University of Marburg in Germany, who is involved in the European effort, is optimistic about the future for people with RBD. He expects that of the dozens of potentially disease-modifying Parkinson’s drugs currently in clinical trials, at least a few will be available soon. “I tell my patients, ‘You’ve come at the right moment,’” Oertel says. “You will be one of the first to get the right drugs.”

Högl has also been involved in another active area of investigation: finding ways to better characterize RBD. Working with Ambra Stefani of the Medical University of Innsbruck and other colleagues, she has been gathering measurements of muscle activity during sleep in people with RBD. They hope that this work will not only help to streamline the diagnosis of RBD but also help doctors to detect the sleep disorder even earlier, in so-called prodromal RBD, where overt dream enactments might not occur, or in people who may have RBD but exhibit only small, difficult-to-detect movements. Their work suggests that the elaborate, violent behaviors seen in RBD are “just the tip of the iceberg,” Högl says. They may occur on one night but not another. Minor muscle jerks in the hands or elsewhere, in contrast, appear to be much more frequent—and a more stable sign because they occur hundreds of times during the night, she adds.

For now there is no cure for RBD or Parkinson’s—but that doesn’t mean there is nothing patients can do. A growing body of evidence indicates that moderate to intense exercise helps to improve both motor and cognitive symptoms of Parkinson’s, and many neurologists already recommend such physical activity to their patients with RBD. “The evidence suggests that the benefits of exercise are more than just symptomatic,” says Michael Howell, a neurologist at the University of Minnesota. “It appears that this actually is helping to protect brain cells.”

Often appearing as a much earlier stage of Parkinson’s disease, RBD provides a chance to intervene when treatments are more likely to be effective.

Both Alda and Merrell have taken that advice to heart. In addition to medications, Alda has taken up exercise-based therapy for Parkinson’s. Merrell, too, has integrated regular physical activity into his routine, hiking for several miles every other day. He’s gotten involved in clinical research and is one of the NAPS participants. This contribution helps Merrell feel empowered—he hopes to aid the discovery of effective neuroprotective therapeutics. “Somebody always had stepped up in other illnesses or conditions that allowed for clinical trials and the therapies that we have today,” Merrell says. “I just happened to be queued up for this—and I accept that challenge.”

FROM OUR ARCHIVES

Does Parkinson’s Begin in the Gut? Diana Kwon; ScientificAmerican.com, May 8, 2018.

scientificamerican.com/magazine/sa

CHANGING the LANGUAGE of CLIMA CHANGE

Natural Gas
= Methane Gas
≠ Clean Fuel

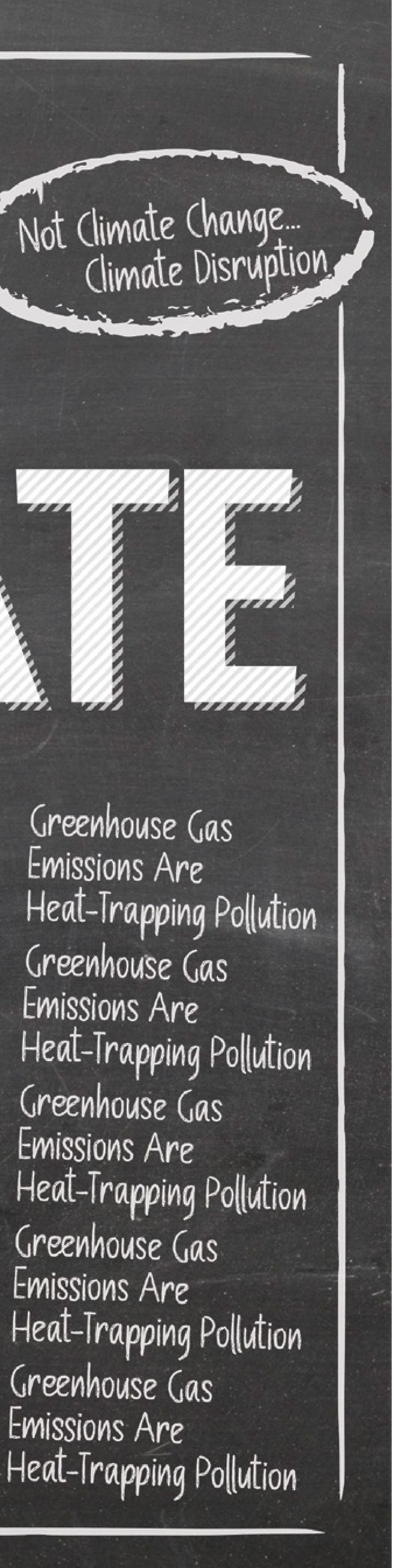
~~Se•ques•ter (verb) to set apart~~

Se•ques•ter (verb) - Lock up carbon over the long term

CULTURE

Choosing words and stories that speak to people's priorities can build the will needed to implement climate solutions

By Susan Joy Hassol



CLIMATE CHANGE IS ALREADY DISRUPTING THE LIVES OF BILLIONS OF people. What was once considered a problem for the future is raging all around us right now. This reality has helped convince a majority of the public that we must act to limit the suffering. In an August 2022 survey by the Pew Research Center, 71 percent of Americans said they had experienced at least one heat wave, flood, drought or wildfire in the past year. Among those people, more than 80 percent said climate change had contributed. In another 2022 poll, 77 percent of Americans who said they had been affected by extreme weather in the past five years saw climate change as a crisis or major problem.

Yet the response is not meeting the urgency of the crisis. A transition to clean energy is underway, but it is happening too slowly to avoid the worst effects of climate change. The U.S. government finally took long-delayed action by passing the Inflation Reduction Act in August 2022, but much more progress is needed, and it is hampered by entrenched politics. The partisan divide largely stems from conservatives' perception that climate change solutions will involve big government controlling people's choices and imposing sacrifices. Research shows that Republicans' skepticism about climate change is largely attributable to a conflict between ideological values and often discussed solutions, particularly government regulations. A 2019 study in *Climatic Change* found that political and ideological polarization on climate change is particularly acute in the U.S. and other English-speaking countries.

One thing we can all do to ease this gridlock is to alter the language and messages we use about climate change. The words we use and the stories we tell matter. Transforming the way we talk about climate change can engage people and build the political will needed to implement policies strong enough to confront the crisis with the urgency required.

WORDS MATTER

TO INSPIRE PEOPLE, we need to tell a story not of sacrifice and deprivation but of opportunity and improvement in our lives, our health and our well-being—a story of humans flourishing in a post-fossil-fuel age.

Some of the language problems we face in presenting this story are inadvertent and innocent, such as how scientists use jargon and think the facts speak for themselves. Others are intentional and insidious, such as the well-funded disinformation campaign led by the fossil-fuel industry that is meant to confuse, obfuscate and mislead.

Jargon can be hard to understand, but even worse are familiar terms that in a scientific context have entirely different meanings. For example, people generally use "positive" to mean "good" and "negative" to mean "bad." But climate scientists use "positive" to mean "increasing" and "negative" for "decreasing." So a positive trend in temperature means it's going up—not good in an era of global warming. Scientists also speak of negative emissions, which sounds like bad pollution but in fact refers to the removal of carbon dioxide from the air—a good thing! It would be clearer to call these efforts CO_2 removal, uptake or drawdown.

Perceptions can be greatly influenced by the words we use. "Natural" commonly refers to things occurring in nature that are not influenced by humans. But many events we call natural disasters—such as torrential rains and more powerful hurricanes that lead to severe flooding or extreme heat and drought that exacerbate wildfires—are no longer entirely natural. By disrupting climate and erecting buildings in vulnerable locations, humans are creating unnatural disasters. The word "natural" can be exploited in other ways, too. In 2021 researchers at Yale University found that Americans associate natural gas with "clean" and methane gas with "pollution"—even though natural gas is almost entirely methane.

The language we use for climate solutions can exacerbate the cultural divide. Terms such as "regulate," "restrict," "cut,"

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"control" and "tax" are unpopular, especially among conservatives. Perhaps people would be more likely to support solutions described with words such as "innovation," "entrepreneurship," "ingenuity," "market-based" and "competing in the global clean energy race." The fact that the first significant U.S. climate policy is called the Inflation Reduction Act is another example of how word choice matters. The name itself helped to gain the crucial support of Senator Joe Manchin of West Virginia, the swing vote. The name may also have made the legislation more appealing to the many Americans who worry about climate change but rank it below inflation and the economy on their list of priorities.

Changing other words can help inform people and redirect the climate conversation. Instead of referring to greenhouse gases, we can refer to "heat-trapping pollution." That term reinforces the basic mechanism of human-caused climate change, and "pollution" has negative associations, which are appropriate in this context. "Climate change" has become pretty standard, but a better description of what we're experiencing is "human-caused climate disruption." Sadly, "climate crisis" and "climate emergency" are accurate, too.

In low-lying coastal areas, seawater increasingly fills the streets at high tide, even on days with no rain. The costs are enormous: cities such as Miami spend hundreds of millions of dollars on systems to pump the water out. Yet experts call this "nuisance flooding," greatly understating its human and monetary impacts. It might more appropriately be referred to as "sunny-day" or "recurrent" flooding. Similarly, as sea level rises and stronger hurricanes hit, we are beginning to hear calls for "managed retreat" from the coasts. But that sounds too much like surrender. As military generals have been known to say, we never retreat; we just advance in a different direction. It would be more positive to call for "proactive relocation" to safer, higher ground.

TAKING ON THE CHALLENGES

WORD CHOICE is part of the broader set of communication challenges we must face to build the political will needed to swiftly address the climate crisis. We can group the challenges into disinformation, misconceptions and the pigeonholing of climate change as an environmental issue. Let's take disinformation first.

BETTER WORDS TO EXPLAIN CLIMATE SCIENCE

SCIENTIFIC TERM	PUBLIC MEANING	BETTER CHOICE
Beach nourishment	Making beaches healthier	Dredging and moving sand repeatedly
Climate change	Any change in climate	Climate disruption
Greenhouse gas emissions	Hothouse exhaust	Heat-trapping pollution
Natural gas	Clean fuel	Methane gas
Negative emissions	Bad pollution	CO_2 removal or drawdown
Nuisance flooding	Inconvenient water	Recurrent sunny-day flooding
Positive feedback	Good response	Self-reinforcing cycle
Sensitivity	Awareness of feelings	Warming from doubled CO_2 concentration
Sequester	Keep jury from news	Lock up carbon over the long term
Retreat	Surrender, give up	Proactive relocation
Extratropical	Especially tropical	Outside of the tropics
Natural disasters	Acts of God, caused by nature	Human-made disasters

The fossil-fuel industry and those who do its bidding have executed a well-funded, long-running disinformation campaign that takes advantage of the confusion around climate language. The people behind this campaign know that scientists use "theory" to mean an idea that is very well established in science, but to the public, a theory is just a hunch. They also know that to the public, "uncertainty" is synonymous with "ignorance," even though scientists use the term to refer to a range of possible results. So fossil-fuel advocates endlessly repeat: "Climate change is only a theory. There's so much uncertainty."

As the climate crisis has increasingly affected our daily lives, it has become more difficult to deny its reality. That's why people guarding the status quo have changed tactics, shifting from denial of climate science to strategies such as deflection—for example, getting us to focus on our own personal carbon footprints rather than examining the huge role of big oil and gas companies in delaying climate action. They also sow doubt by promoting myths and lies about solutions—they're too expensive, they're unreliable. Donald Trump told a crowd in 2019 that if a "windmill" were erected anywhere near their house, their home value would drop 75 percent, and the noise would cause cancer.

One way to counter disinformation is to get ahead of it by "inoculating" the public—promoting accurate information and helping people recognize disinformation techniques. Researchers have determined that preemptive messages explaining disinformation techniques while highlighting correct information can be effective in preventing misunderstanding. One key fact to emphasize is that the cost of renewable energy has plummeted, making clean energy cheaper than dirty energy. The prices of solar power and batteries have fallen by about 90 percent in the past decade, and there have been steep declines in the cost of wind energy as well.

Good progress has also been made on managing variable energy sources such as solar and wind, as well as in storing the energy they produce. We're not waiting for an energy miracle; we've already had one.

The second major challenge, often related to the first, involves widespread misconceptions about climate disruption and public perception. Research published in 2022 in *Nature Communications* showed that although 66 to 80 percent of Americans support climate change policies, they *think* only 37 to 43 percent of the population does; they believe the climate-concerned community is a minority, when in fact it's a majority. The researchers also found that although supporters of policies to limit climate change outnumber opponents two to one, Americans falsely perceive the opposite to be true. This false social reality tends to limit how much people talk about the subject, and it decreases motivation and political pressure to pursue climate policies. One response is simply to talk about climate change more with family, friends, co-workers, and leaders in the public and private sectors. Each of us can be part of this solution.

There's also a growing misconception that it's too late to act—that global climate catastrophe is inevitable. This may result, in part, from the media's focus on disasters rather than solutions, which can make many people feel a sense of hopelessness or fatalism. A 2021 study in the *Lancet* revealed that young people are especially vulnerable to these feelings, with 84 percent saying they're worried and 75 percent saying they think the future is frightening. If people are convinced we're doomed—that there's nothing we can do—why would they bother trying? It is imperative that we clearly communicate that it is not too late to avoid the worst outcomes. We must act urgently because every delay means a hotter and costlier future. Every fraction of a degree matters, and every action matters. As climate activist Greta Thunberg of Sweden so aptly put it, "When we start to act, hope is everywhere."

People who feel constructive hope (as opposed to passive hope, such as that "God will save us") are more likely to act and support climate policies, according to a 2019 study by researchers at Yale and George Mason University. Raising feelings of hope involves boosting a sense of efficacy—that what we do as individuals and as a society can truly make a difference. Rather than promoting stories of doom and deprivation, we can tell stories that illustrate the many benefits we will reap from the clean energy transition and from protecting nature. We need to paint a picture of that better world—powered by renewable energy, with friendlier, more walkable cities—and show how and where the improvements are already unfolding. It's psychologically important for people to know that we're not just starting; we're already on our way.

The third challenge is that climate disruption has for years been categorized as an environmental issue. A 2021 Gallup survey found that only 41 percent of Americans consider themselves environmentalists. And environmental issues, especially climate change, have become so politically polarized that some people are hostile to any discussion of them.

HOW TO TALK WITH PEOPLE ABOUT CLIMATE CHANGE

1. Make it personal
2. Appeal to people's priorities
3. Connect on values
4. Find common ground
5. Address the here and now
6. Focus on extreme weather
7. Promote clean energy
8. Emphasize cost savings
9. Stress the urgency of action
10. Show where action is working
11. Highlight our choice of futures

The reality is that everyone cares about something affected by the climate emergency. Are they people of faith? Climate disruption is damaging God's creation and disproportionately hurting people who are "the least of these." Do they like to fish? Climate change is warming up our rivers, reducing the habitat for cold-water species such as salmon and trout. Are they skiers? Warming is reducing winter recreation opportunities. Everyone has to eat, and climate change is taking a toll on some of our favorite things, such as coffee and chocolate, as well as important staple crops, including corn and wheat. Many people are suffering from rising summer heat and humidity, wildfire smoke, and other aspects of increasingly extreme weather. The next time you want to talk with someone about climate disruption, consider what they care about and use that as an entry point. As with most good communication, success depends on the ways we connect on values, build trust and find common ground.

If you know that someone's group allegiance leads them to reject the notion of human-caused climate change, rather than banging your head against a locked front door, look for a side door. For example, almost everyone likes clean energy, and for good reason. It offers clean air and water, energy security, reduced costs, job creation, and more. So even without invoking climate change, there are many reasons to support deploying clean energy. A 2015 study in *Nature Climate Change* showed that across 24 countries, action on climate change was motivated by other benefits, notably economic development and healthier communities. A 2022 study in *Nature Energy* compared three ways of framing renewable energy's benefits—cost savings, economic boost and climate change mitigation—and found that cost savings was the most effective frame across political groups. One ironic example: in 2017 the Kentucky Coal Museum covered its roof with 80 solar panels because the technology saved the organization money.

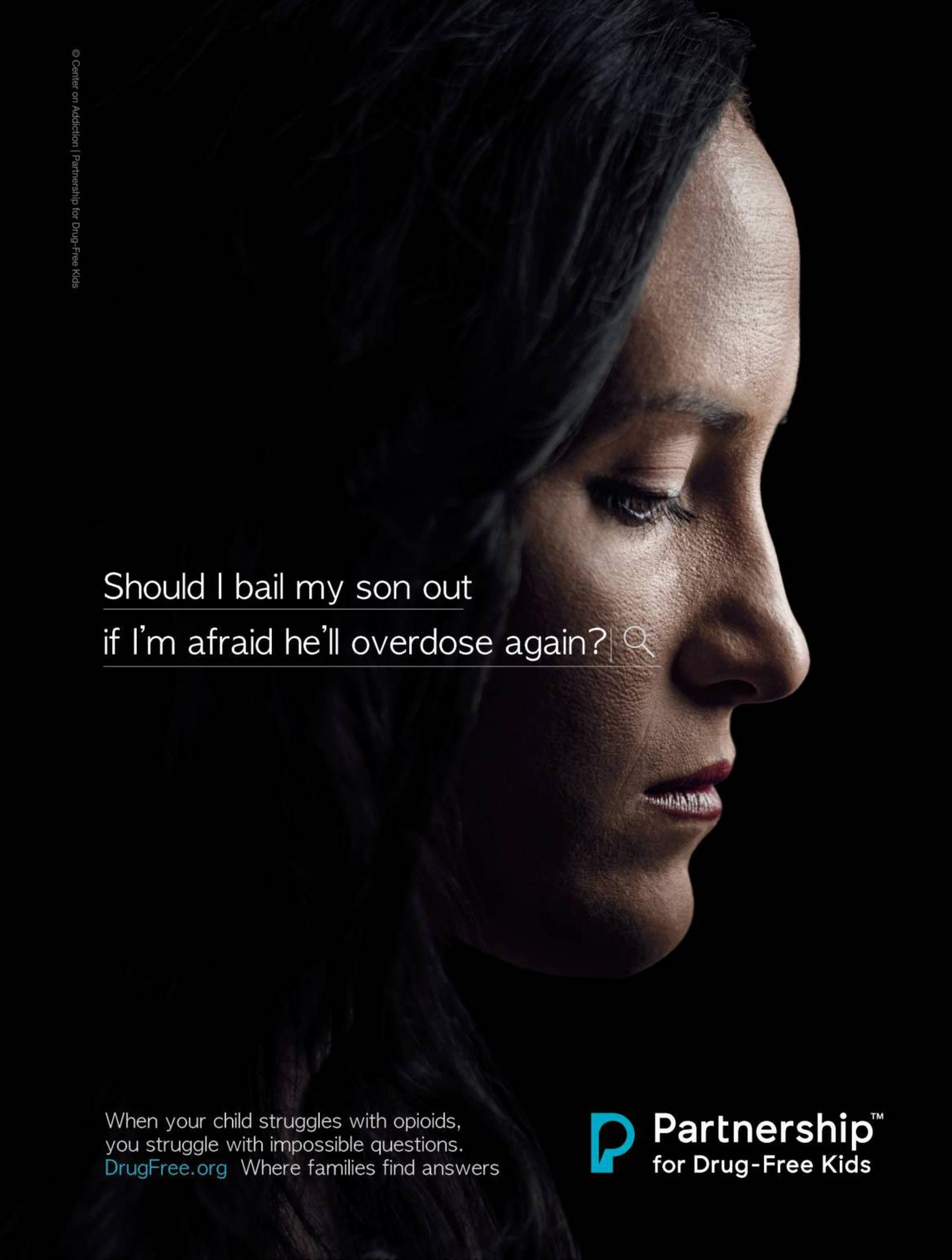
Making the changes necessary to avoid the worst impacts of climate disruption will require sufficient social support before the world crosses too many dangerous climate thresholds. Research published in 2018 in *Science* suggests large-scale social changes require the active engagement of about 25 percent of the population. Surveys suggest that in the U.S. we are rapidly approaching that point on climate. Researchers at Yale and George Mason found that as of late 2021, one third of Americans were alarmed about the climate crisis, and most of them were willing to act.

Addressing climate communication challenges could help us build enough political will in time to blunt the worst climate change effects. People must grasp the urgency of the choice we face between a future with a little more warming and global catastrophe. And they need to recognize that the choices we make now will determine our fate.

FROM OUR ARCHIVES

False Hope. Michael E. Mann; April 2014.

scientificamerican.com/magazine/sa


Should I bail my son out
if I'm afraid he'll overdose again?

Margarita Leib is an assistant professor at Tilburg University in the Netherlands, where she studies ways that people's interactions—with one another and with artificial intelligence—shape ethical behavior.

Collaboration's Dark Side

Working together can make it more tempting for groups to lie and cheat

By Margarita Leib

Groups of engineers at Volkswagen, working on cars sold between 2008 and 2015, faked engine emissions levels during laboratory tests so the cars could meet low pollution standards. But when the cars hit the road, their real emissions were much higher. The scam, dubbed "Dieselgate," had severe consequences. The additional pollution in the U.S. alone could contribute to dozens of premature deaths.

Dieselgate is one example of what researchers call collaborative dishonesty. Often discussion of collaboration emphasizes its advantages: it helps people solve complex problems they could not address alone, for instance. But there are also situations in which group work can be fertile ground for dishonest behavior.

My colleagues and I pooled data from many past studies to understand the forces that shape and underlie group dishonesty. We analyzed 34 research projects that involved more than 10,000 participants altogether. In these experiments, scientists asked people to play economic games or carry out decision-making tasks while part of a team. The specific instructions varied from one study to the next, but across experiments, participants could gain money through honesty and teamwork.

They also had opportunities, however, to earn additional money as a group by lying. For example, in some tasks, teams received a payout based on the number of puzzles they solved together; participants could lie and inflate the quantity they had deciphered. Across all studies and tasks, we found that groups tended to lie. On average, they earned 35.6 percent of the extra profits available to them above what they could make from simply telling the truth.

We also showed that collaborative dishonesty is contagious and escalates. Several studies we analyzed involved asking pairs of people to roll dice over multiple rounds. One person rolled a die in private and then reported the outcome. Their partner learned about that report and then rolled an independent die before reporting their own outcome. If both teammates claimed to have rolled the same number, they received a payout: for example, a one-one double might mean each person got $1, a two-two double could mean $2 each, and so on. Pairs could choose to be honest and receive payment only when they truly rolled doubles. But over the course of many rounds, some pairs would be tempted to falsely declare a higher or matching roll for greater or more frequent payouts.

For these studies, we first identified whether any participants were obviously deceitful. When the data suggested that certain people reported only sixes—the highest roll possible—or only doubles in all rounds of the task, we labeled these improbably lucky rollers as brazen liars. (Because the chance of getting sixes or doubles in 20 rounds, the most common number of rounds in the task, is very small—less than 0.001 percent—we felt confident about this classification.)

The brazen liar's behavior influenced their partner. People were more likely to lie when their partner did. This dishonesty also grew over time. In later rounds, compared with earlier ones, the first person to roll a die was more likely to report a higher roll, and their partner was more likely to report a double.

The good news is that there was a limit to the deceit. In puzzle tasks, for instance, most teams did not pretend to solve every puzzle presented. And when studies added ethical costs for dishonesty, such as by informing people that lies would harm other participants or have negative consequences for a charity donation, groups lied less. On top of that, we discovered that the gender and age of the group members mattered. The more women a group had and the older its members were, the less the group lied. We are still investigating reasons for this pattern.

Our findings point to specific ways people could encourage honesty when groups work together. For instance, our discovery that collaborative dishonesty is contagious suggests that people should try to detect and act on early signs. Managers could implement zero-tolerance policies toward even small acts of deceit to deter its spread. To increase early disclosure of dishonesty, they could put policies in place that forgive whistleblowers for their part in wrongdoing when they come forward about dishonest deeds. And because groups are more honest when they believe others are harmed by their lies, highlighting the negative consequences of dishonesty more prominently may help curb it. SA

Illustration by Jaimie Shelton

JWST Glimpses Dazzling Stellar Spirals

A new image of a star surrounded by strange swirls reveals a hidden chapter in the story of the cosmos

By Phil Plait

One of the more poetic aspects of the universe is that frighteningly powerful and raging forces can sculpt objects of graceful symmetry and beauty. And, as an added bonus, such forces may also lend a hand in our own existence.

WR 140 is a binary-star system, meaning two stars orbiting each other, some 5,400 light-years from Earth. Both stars are absolute beasts, blasting out fierce amounts of light, but across that astronomical distance their brilliance is diminished to naked-eye invisibility.

The James Webb Space Telescope (JWST), however, has far keener eyesight than we mere humans, plus it peers at the cosmos in infrared wavelengths far beyond what our eyes can see. Astronomers recently pointed JWST at the twin stars in WR 140, and what it witnessed was absolutely spectacular.

Astronomers have long wondered if grains of cosmic dust can form in and escape from the harsh inner regions of violent stellar systems. These JWST observations of WR 140 reveal that the answer is yes. This entire structure is at least two light-years (or 20 trillion kilometers) in diameter—and probably even more because there are likely fainter arms farther out that lie beyond the reach of these JWST observations. Just accounting for the visible arms, this structure surrounding WR 140 is the largest of its kind ever seen, four times the width of the next bigger known one.

The rippling spiral almost looks like a defect in the telescope itself, some strange optical phenomenon affecting the observations. But it's very real, despite what its gossamer appearance suggests: As described in a paper published in November 2022 in the journal *Nature Astronomy,* this eye-catching construct emerges from the clash of immense forces flinging vast amounts of matter into space at soul-crushing speeds, powered by stars that make our own sun look like a flashlight with dying batteries. And you can set your watch by it. Or at least your calendar.

Each star in the WR 140 binary system is far more massive than the sun. One lies at the upper range of what can be called a normal star—that is, one that shines by fusing hydrogen into helium in its core, just as our own star does. At 30 times the sun's mass, it's a monster and monstrously luminous, radiating energy at a rate a million times that of our sun. Replace the sun with this star in the center of our solar system, and Earth would get cooked.

The other component of WR 140 gives the binary system part of its name; it's in a special class of stars called Wolf-Rayet (WR). It probably started its life with 20 or more solar masses but eventually ran out of usable hydrogen in its core and is now instead furiously fusing helium into carbon. Fusing helium rather than hydrogen liberates much more energy, which disrupts the star's delicate equilibrium between its gravity trying to collapse it and its infernal heat trying to make it explode. This causes it to blow material out into space at a truly fantastic rate. The resulting windy maelstrom has carried off fully half the star's original mass—we're talking something like *20 octillion tons* here, a nearly unfathomable amount—leaving the star with only (*only*) 10 times the sun's bulk. It's roughly half as luminous as its companion, which still makes it a radiation powerhouse.

In fact, the other star is also expelling a wind of particles, though at a substantially lower rate than its Wolf-Rayet companion. These two winds slam into each other as they expand away from their respective stars, and it's this cosmic collision that forms the spiral pattern in the JWST image.

Researchers have spied this kind of structure before in Wolf-Rayet binaries, but WR 140 is different because its two stars are on a highly elongated elliptical orbit. Their separation ranges from about four billion kilometers to only 200 million kilometers apart—about the distance of Neptune and Mars from the sun, respectively.

When the stars are at their most distant from each other, their winds expand relatively freely, but every 7.93 years they come so close together in their orbit that the winds begin to interact strongly. Mind you, these winds blow at nine million kilometers per hour. Their collision at that speed generates powerful shock waves, which act a bit like a hammer pounding the material within.

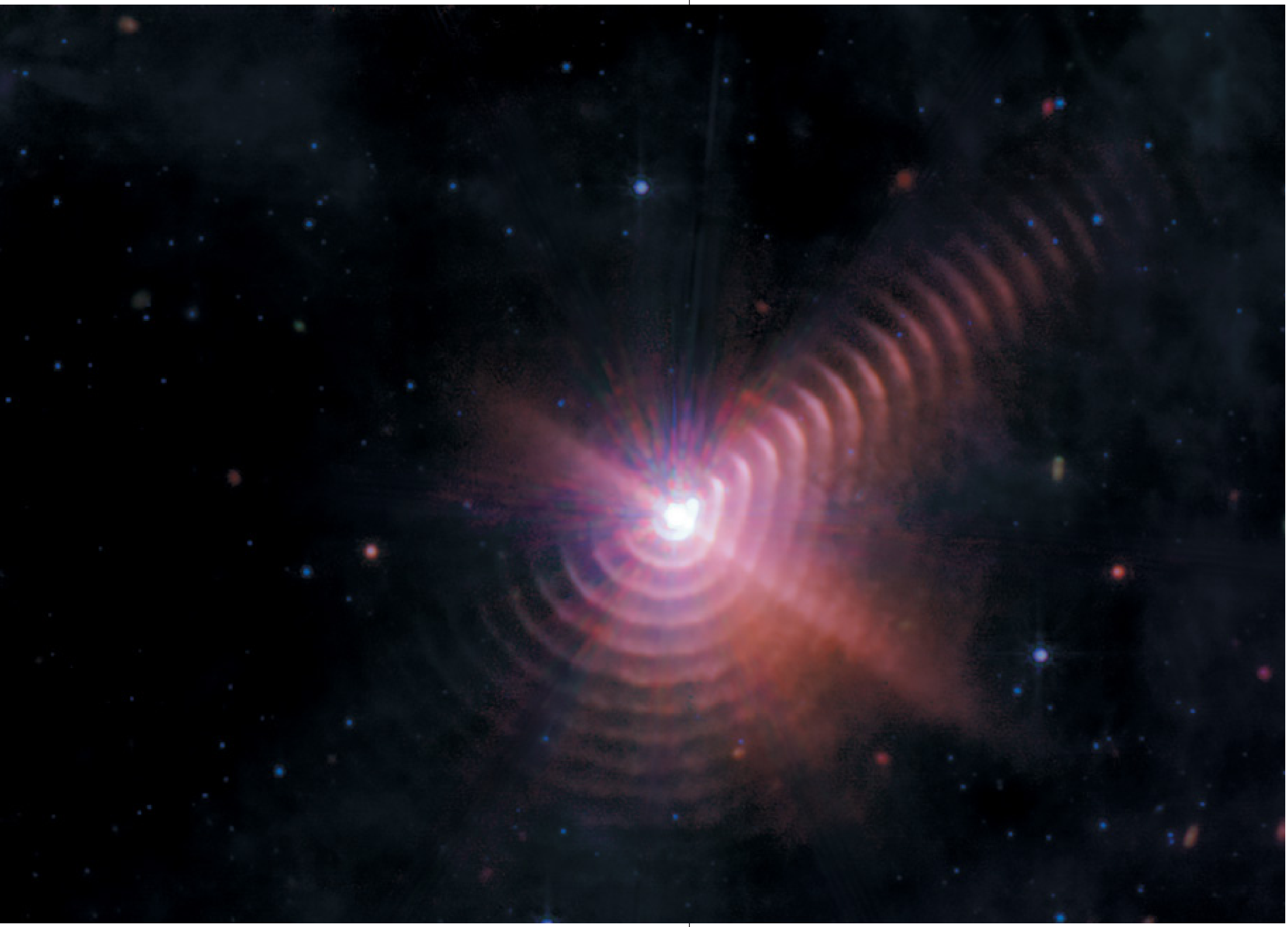
Observers studying WR 140 with ground-based telescopes had already shown that the Wolf-Rayet star's wind is heavily laced with carbon dredged up from the stellar core. When the collisional shock wave sweeps over that carbon, the atoms rearrange themselves into complicated molecules called polycyclic aromatic hydrocarbons, or PAHs. Astronomers generically call this material dust.

The expansion of the winds plus the orbital motion of the stars makes their interaction geometrically complex. Using computer models to simulate the physics of the situation, the astronomers in the new work have reproduced in remarkable detail the structures seen in the JWST image.

What they found is that the collision stirs up most of the dust just before and after the stars' closest approach to each other but not during that closest approach, when the cumulative effects of stellar winds and radiation overpower dust formation. This leads to two pulses of dust creation and ejection, which we see as long streamers flying away from the point of contact much like plumes of sand flung off a sharply turning dump truck.

Moreover, this process repeats like clockwork every orbit, each time spewing twin sprays of expanding material as the stars approach each other. Every set of sprays has nearly eight

Phil Plait is a professional astronomer and science communicator in Colorado. He writes the *Bad Astronomy Newsletter*. Follow him on Twitter @BadAstronomer



Infrared JWST observations of the WR 140 system show a huge and complex spiral structure of gas flowing away from the stars in the center.

NASA/ESA/CSA/STScI/JPL-Caltech

years to fly away at high speed, moving well over 600 million kilometers before another set emerges, creating a rippling pattern of dusty arms and rarefied gaps. Shortly after its formation, this dust is warm, making it visible to JWST's infrared instruments, which see the thermal glow of its heat. But as the arms expand away, they cool and fade, which is why the outer arms look dimmer. Close inspection reveals 17 such spiral arms in the JWST image, with incomplete arcs marking older, colder and more distant ejecta.

The breadth of the repeated spiral patterns—starting practically on top of the stars and stretching so far away from them—indicates this dust originates near the stars and then travels to the depths of interstellar space, something astronomers weren't sure could occur in such a system. And that means similar binary stars can account for a large fraction of the dust we observe in our galaxy.

Much of that dust is located in enormous clouds of gas that can eventually collapse to give birth to vast numbers of stars. These star-forming factories are all over the Milky Way, making it likely the sun was born in one as well. In fact, some prior research suggests that the winds from a nearby Wolf-Rayet star can actually trigger such a cloud's collapse and may have done so in the case of the sun.

The brutal fury of a system like WR 140 is undeniable, from the incredible luminosities of its stars to the cosmic tsunami of dusty winds they blast away. But there is order in that chaos: the laws of physics sculpting a pattern vast and lovely, a glowing pinwheel we can see across the interstellar abyss that may have a connection to our own cosmic origin.

That dust will mix with older material floating in space and may one day cause and be a part of the creation of new stars, some of which may very well start the pattern again. Poetry indeed. SA

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REVIEWS

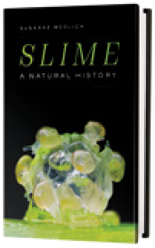
Edited by Amy Brady

NONFICTION

Sublime Slime

In awe of substances that ooze

Review by Michael Welch



Slime: A Natural History
by Susanne Wedlich. Translated by Ayça Türkoğlu. Melville House, 2023 ($27.99)

In *Slime: A Natural History,* science journalist Susanne Wedlich preempts her readers' repulsion. Although "we are all creatures of slime," she writes on page 2, the mere mention of the name connotes images of sickness, death, and other taboo experiences of modern, "hyperhygienic" life that we often try to keep unspoken and out of view. Wedlich intends to change the perception of slime from something that disgusts to something that fascinates.

In this way, the book quickly takes on a persuasive tone, with Wedlich dismantling negative preconceptions. A literary and sociological analysis of slime visits references from movies such as *Alien* and *Ghostbusters* and Vladimir Nabokov's novel *Lolita,* where it's a metaphor for "everything that can be dangerous, disgusting and simply wrong about sex," to the campaign for sanitary reform in the 19th century and our aversion to powerful odors as an indication of uncleanliness.

This compelling cultural overview beckons readers toward the more science-heavy parts, where things get a bit stickier. Defining what slime *is* "may be as slippery as the substances themselves." Although mud and muck were thought of as a source of life by the ancient Egyptians, it wasn't until Darwinist Ernst Haeckel hypothesized that primordial slime on the ocean floor contributed to the origins of life that the study of slime gained some attention.

To this day, many biological slimes haven't been researched enough to know the details of their structure and behavior. The general qualification that they exist between fluids and solids allows Wedlich to take a wide view: "If it looks like slime, behaves like slime, is regarded as slime or simply catches my attention in a slime-like way, it belongs in this book."

This smart decision shapes the stories that follow. We hear about snails that surf their own mucus for forward propulsion, digestive secretions that help defend our bodies through a mucosal immunity, and bioadhesives that create "marine snow," a continuous shower of organic rain that delivers energy to the deep ocean. Wedlich's knack for unfolding these natural histories makes her book ooze with charm.

IN BRIEF

The Darkness Manifesto: On Light Pollution, Night Ecology, and the Ancient Rhythms That Sustain Life

by Johan Eklöf. Translated by Elizabeth DeNoma. Scribner, 2023 ($26)

As a Swedish conservationist, Johan Eklöf urges us to think of light pollution as more than a nuisance that obscures our starry skies. In a series of well-researched vignettes, his message is a plea for nonhuman species: artificial lights disrupt migration patterns, mating rituals, pollination practices, insect biomass, and much more. Eklöf highlights the startling sprawl of these lesser known consequences without evoking a hopeless or cynical tone. Instead the book is a reflective reminder that our control of the world is as delicate as the smallest of species affected by it. *—Sam Miller*

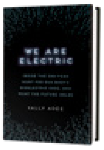
Wilderness Tales: Forty Stories of the North American Wild

edited by Diana Fuss. Knopf, 2023 ($35)

Featuring writers such as James Fenimore Cooper, Karen Russell and Anthony Doerr, this anthology charts a modern course through a long-established genre. The unconventional selection of wilderness stories takes us from swamp to tundra and from Plymouth Rock to today's crisis point in the Anthropocene as it maps the complex evolution of our society's relationship with wild places and the shifting tales we tell about them. Although editor Diana Fuss organizes the book around themes as divergent as "Fire and Ice" and "Women and Panthers," every story asks us to reexamine "what wilderness may mean and why it compels us." *—Dana Dunham*

We Are Electric: Inside the 200-Year Hunt for Our Body's Bioelectric Code, and What the Future Holds

by Sally Adee. Hachette Books, 2023 ($30)



A decade ago, when a researcher sent an electric current through journalist Sally Adee's brain, she momentarily became a sharpshooter in a simulated military operation. The experience left Adee with a lot of questions. In her debut book, she paints a riveting (and often humorous) picture of 200 years of research on the bioelectricity coursing through our bodies, from debates over twitching frogs' legs to devices developed to give sensation back to people with traumatic nerve injuries. In this bioelectric age, Adee argues, "we are electrical machines whose full dimensions" are ripe for discovery. *—Fionna M. D. Samuels*

Illustration by London Ladd

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *Discerning Experts* (University of Chicago, 2019).

Let's Get Real

"Realists" say oil and gas won't go away soon. Our climate is doomed if they don't

By Naomi Oreskes

Toward the end of 2022, I was a panelist at a session on climate change held by a major scientific society. Near the end of the session, a prominent scientist declared that we needed to be "realistic": oil and gas weren't going away anytime soon, and we had to accept that as we attempted to solve our climate crisis.

The oil and gas industry makes this argument all the time, of course, but lately I've heard it from scientists such as the person at that meeting. Even some environmentalists make it when they have accepted the idea that natural gas needs to be a "bridge fuel." But carbon pollution from burning oil and gas (and coal)—along with deforestation and animal agriculture—is the cause of the climate crisis. Is it realistic to think you can solve a problem while continuing to do the very thing that caused it?

Some years ago I gave a college commencement address entitled "Don't Be Realistic." To the graduating students in front of me, I said that pleas for "realism" are often used to discourage those who think the world can be a different place. The people making them want to justify the status quo and deflate the ambitions of those among us who would be agents of change. The argument for realism in dealing with climate change is one of those calls for inaction. It is an excuse to resist change.

This is not the only time in history that the U.S. has been asked not to change. This country was founded as a nation partly enslaved. At the Constitutional Convention, there were bitter battles over whether a nation conceived in liberty and dedicated to the proposition that all people are created equal should permit one segment of its population to remain in bondage. Those who argued for the preservation of slavery insisted its abolition was simply not realistic.

Eighty years later, when Abraham Lincoln confronted the issue of emancipation, he also faced the realist argument. It wasn't realistic, some said, to think formerly enslaved people could become self-sufficient members of a republic or that society was ready to embrace them as citizens. In some ways, the realists making that second point were right: After taking nearly a century to abolish slavery, the U.S. took another one to legally abolish its residues of enforced segregation, physical violence and grosslyw unequal protection under the law. When Martin Luther King, Jr., marched on Washington, D.C., in the 1960s to gain civil rights, he was advised not to push too hard. He was counseled to go slow.

But it was his very unrealistic expectation—the outrageous belief that it was possible to have a country that practiced what it preached, a country where all people and not just white males were not only created equal but treated equally—that led to change. That unrealistic expectation helped to bring about a new reality.

The truly realistic solution to climate change is "deep decarbonization"—reorganizing our energy systems to rely on technologies that do not cause carbon pollution. We have to start this work immediately and cut emissions in half by 2030 to keep global temperatures from rising more than 1.5 degrees Celsius—a threshold beyond which catastrophic damage is almost certain to occur, according to recent scientific analysis.

To accomplish this goal, we should focus our attention on proven technologies that can do the lion's share of the job. This means rapid expansion of wind and solar, supplemented by hydropower, biomass reactors and existing nuclear energy. It also means developing policies that encourage energy efficiency. It means focusing our research dollars on energy storage and improvements to the electricity grid required to maximize our use of the wind and the sun.

And it means not getting distracted by promises of breakthroughs that may or may not come on time. (Computer scientist John Mashey, who worked at Bell Labs—one of the greatest centers of innovation in the mid-20th century—says they had a slogan: "Never schedule breakthroughs.")

Conventional realism asserts that we cannot live any other way than the way we do now. The fossil-fuel industry asserts that we cannot live without its products. But history shows that humans have lived and thrived in many different configurations. It is not unreasonable to think we could, in the future, live in a less destructive manner than we do now. And if that aspiration appears to be unrealistic, then we need to find strategies to make it real. SA

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Illustration by Aad Goudappel

50, 100 & 150 YEARS AGO

INNOVATION AND DISCOVERY AS CHRONICLED IN *SCIENTIFIC AMERICAN*

Compiled by Mark Fischetti

FEBRUARY

1973 Mount Everest Not the Highest

“According to Robert L. Birch, the highest mountain is probably Chimborazo in the Ecuadorian Andes. It all depends on what is meant by ‘high.’ Mount Everest rises 29,028 feet above sea level, Chimborazo 20,561 feet. But because the earth is an oblate spheroid, the sea level at the Equator is some 14 miles farther from the center of the earth than the sea level at the North Pole. Indeed, distance from the center of the earth would seem to be a more reasonable standard for the height of a mountain, since it is a measure of how far the mountain sticks out into space. On this basis Chimborazo, which stands within two degrees of the Equator, is some two miles higher than Everest, which is nearly 28 degrees from the Equator.”

The Paranoid Computer

“‘Doctor: Are you depressed? Patient: No. Doctor: Were you taking drugs? Patient: No. Doctor: What is your problem? Patient: People make me nervous. Doctor: How do they do that? Patient: They stare at me. Doctor: Why? Patient: Maybe they don’t like the way I look or something. Doctor: Do you look unusual in some way? Patient: Why are you interested in my looks?’ This dialogue is the first part of a diagnostic interview between a psychiatrist and a patient who has systematized delusions of persecution. Unknown to the psychiatrist, however, the patient is a computer programmed to simulate paranoid processes in human beings. Out of 25 psychiatrists who interviewed the computer model, 23 judged the patient to be paranoid.”

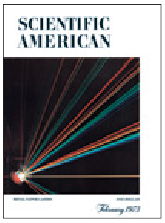
Creationism in Science Class

“Divine creation will apparently not be taught in California as an alternative to evolution, at least not in natural-science classes. After some years of controversy the State Board of Education has decided that creationism need not be given equal treatment with biological evolution in elementary school textbooks. Instead, social science textbooks will have to include discussions ‘concerning the representative philosophies of the origin of man.’”

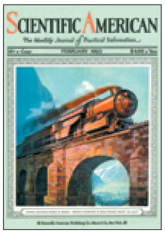
Scientific American, Vol. 228, No. 2; February 1973

1923 Electric Car Has Advantages

“Recently a manufacturer in Wurttemberg, Germany, introduced a new electrically driven small automobile. It is claimed to possess certain advantages. It can be operated more cheaply with electrical power than [cars] with liquid fuels. The driving mechanism, connecting the motor with the wheels, is much more simply constructed. The upkeep is less costly, likewise, and the care that has to be given is by no means as great. The car is started by simply pulling a lever alongside the driver’s seat. The car travels at a maximum speed of 20 to 30 kilometers per hour and can travel 80 to 100 kilometers and return on a smooth, level road. During the night it may be connected with any source of direct current to be recharged. Alternating current can be used as well, when a suitable device is interposed between the battery and the source of current.”



1973



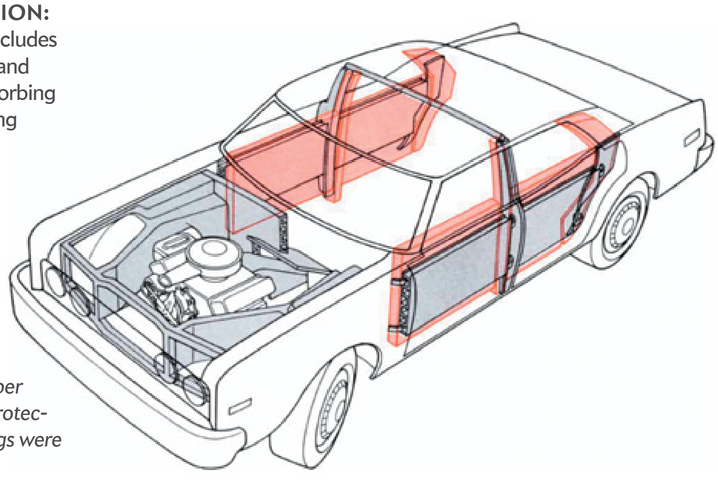
1923

1873

1873 Hudson Ice Cakes for New York City

“In New York the harvesting of ice is at its height on the Hudson River, along whose banks many very large and costly ice houses are found. Thirty thousand tuns are commonly stored in a building. Ice is first scraped and planed across three or four acres near the house, then [sawed] into blocks or cakes 22 by 32 inches, and in some places 44 inches square. Then a canal is cut from the sawn acres to the mouth of the elevators at the house. Polemen shove the ice along till it reaches the elevators, which are worked by steam and convey it to open slideways on each floor of the building, where stowers stand ready with hooks to pack it away. Each house manages to stow away thirty cakes of ice per minute, each cake weighing about 250 pounds. This is 18,000 cakes per day, and there are forty-two ice houses on the river. The total stored for our city market is one million five hundred thousand tuns, being almost one tun of the crystals for every inhabitant of New York and Brooklyn.”

1973, CRASH PROTECTION: “New automobile frame includes [structure] changes (*gray*) and the addition of energy-absorbing material (*color*). The slanting structure at the rear of the engine is to deflect the engine toward the ground, rather than into the passenger compartment, in a head-on collision.” *In late 1997 and 1998 the U.S. began requiring front-seat airbags in passenger vehicles. In September 2013 greater side-impact protection was required, but airbags were not specified.*



GRAPHIC SCIENCE

Text by Tanya Lewis | Graphic by Amanda Montañez

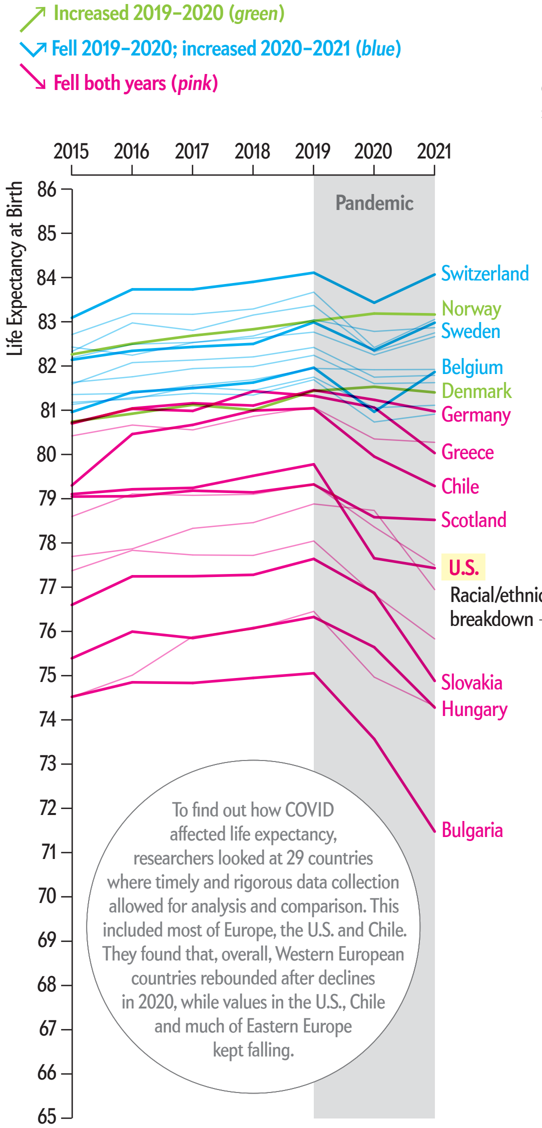
How the U.S. Lost Years of Life

Life expectancy dropped during the pandemic but bounced back in some places

Over the past century people have been living longer lives around the globe. Then COVID hit. Now, nearly three years into the pandemic, with highly effective vaccines widely available, life expectancy in many middle- and high-income countries has started to bounce back. But in the U.S., it is still dropping. A study last year found that life expectancy in most Western European countries recovered in 2021—most likely the result of high vaccination rates that reduced mortality, particularly among the elderly. But the U.S. has continued to see declines, in part because of lower vaccination rates as well as a devastating opioid epidemic.

Despite being one of the richest countries in the world, the U.S. has seen life expectancy fall to a level not documented since 1996, according to an analysis by the Centers for Disease Control and Prevention. And the effects are not felt equally: Native Americans, Black people, Latino people, and men in general have died at disproportionately high rates during the pandemic, from both COVID and other causes.

LIFE EXPECTANCY TRENDS BY COUNTRY

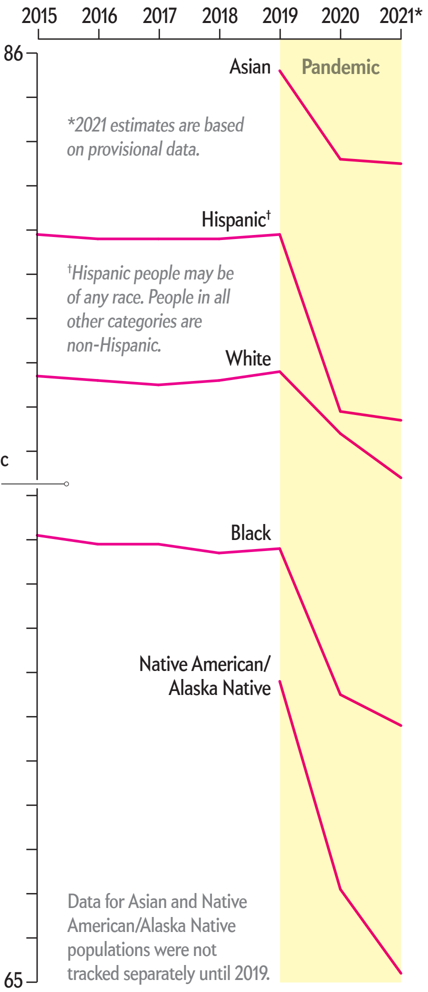


To find out how COVID affected life expectancy, researchers looked at 29 countries where timely and rigorous data collection allowed for analysis and comparison. This included most of Europe, the U.S. and Chile. They found that, overall, Western European countries rebounded after declines in 2020, while values in the U.S., Chile and much of Eastern Europe kept falling.

FACTORS THAT SET THE U.S. APART

Race and Ethnicity

Life expectancy varies significantly among different racial and ethnic groups in the U.S. All groups experienced declines during the pandemic, but some suffered much more than others.



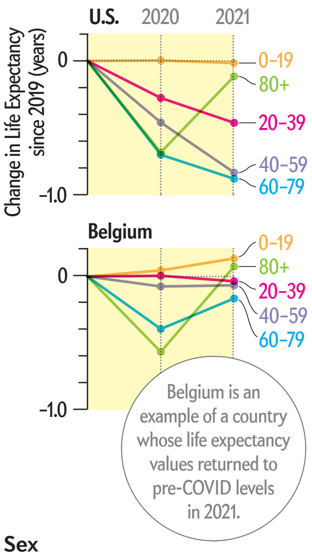
*2021 estimates are based on provisional data.

†Hispanic people may be of any race. People in all other categories are non-Hispanic.

Data for Asian and Native American/Alaska Native populations were not tracked separately until 2019.

Age

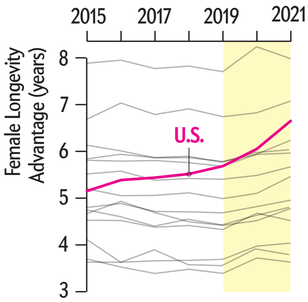
The U.S. did not recover like other countries did in 2021 largely because deaths among people outside the oldest age group kept climbing, despite availability of COVID vaccines.



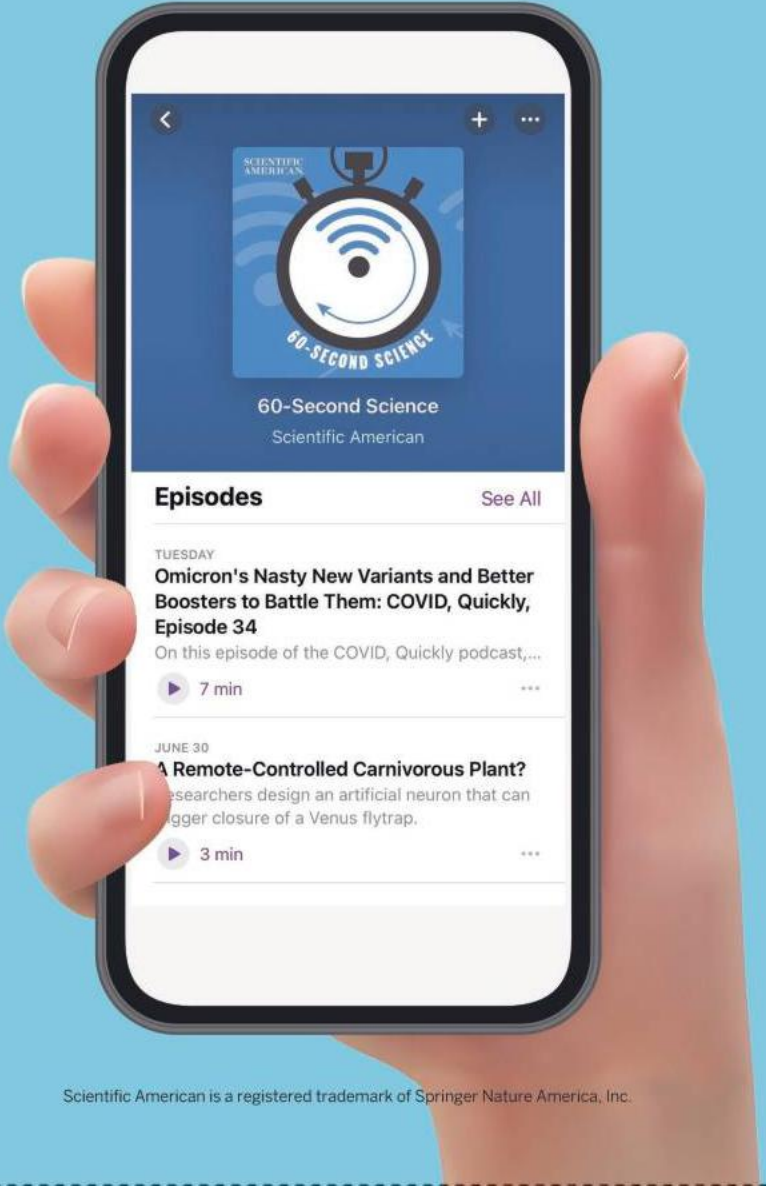
Belgium is an example of a country whose life expectancy values returned to pre-COVID levels in 2021.

Sex

Women tend to outlive men in general. Since 2019, this effect increased in most countries that were tracked, but the gap grew most of all in the U.S.



Sources: "Life Expectancy Changes since COVID-19," by Jonas Schöley et al., in *Nature Human Behaviour*. Published online October 17, 2022 (*country data*); Centers for Disease Control and Prevention (*race and ethnicity data*)



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