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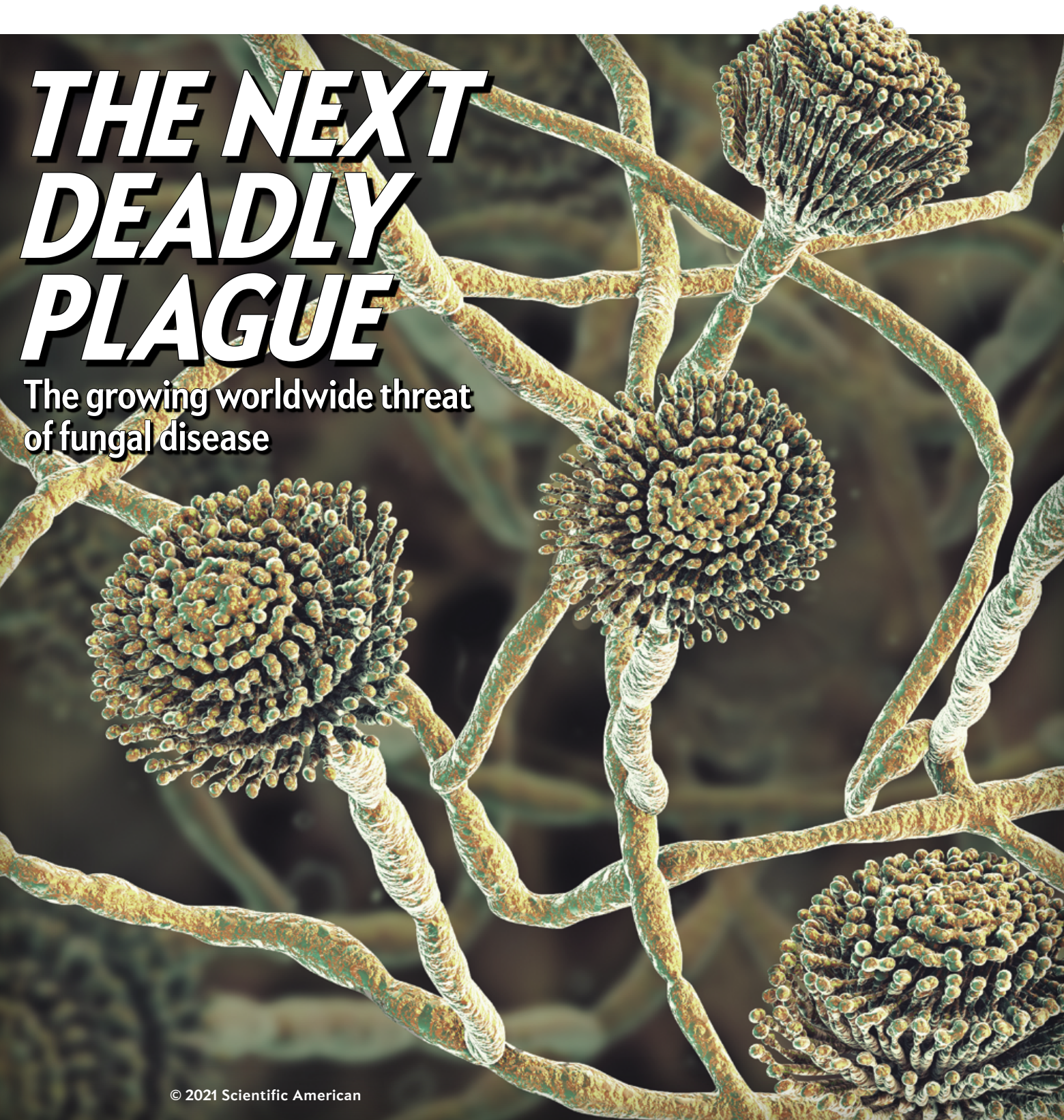
Defending Earth
against Asteroids

Upheaval in
the Arctic

100-Million-Year-Old
Microbes Resurrected

THE NEXT DEADLY PLAGUE

The growing worldwide threat
of fungal disease



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Computer illustration depicts the fungus *Aspergillus fumigatus*, which can cause serious disorders in people with compromised immune function or other lung diseases. The fungus can also spread to the brain, kidneys, liver and skin. Illustration by Kateryna Kon, Science Source.

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ATEM Mini Pro model shown.

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

Fascinating or Disturbing?

What do you think of this month's cover image? We had a bit of a debate about it here at *Scientific American's* virtual HQ. The illustration is based on scanning electron microscope images of *Aspergillus fumigatus*, a ubiquitous fungus that can infect the lungs. The intricate, other-worldly structures look really cool. But some people might reasonably think they're also kind of gross. After all, we recoil from a moldy piece of fruit or the smell of mildew, and as author Maryn McKenna reports, starting on page 26, fungal infections are a terrifying health menace.

We decided the cool-to-gross ratio justified using the image, and we hope it intrigues you. The discussion got me thinking about how people who appreciate science—including our readers and I'd say all of us on the magazine staff—might have a higher tolerance for images or ideas that others find unsettling. The universe isn't just expanding, but it's expanding at a faster rate all the time? Tell us more! The human body contains more microbial cells than human cells? Fascinating. Beady-eyed, buzzy cicadas spend 17 years in a hole in the ground and then emerge by the billions? Show us their life stages and how they do it because that's amazing.

If you're in Brood X territory this summer, I hope you enjoy the cicada eruption as much as the [bug-eating birds will](#). On page 54, senior editor Kate Wong and illustrator Cherie Sinnen present the bizarre life history of 17- and 13-year cicadas. Multiple species coordinate their hatches to overwhelm predators and produce a glut of offspring that will spend most of their lives underground before they emerge for a few weeks of liberation and screeching and desperate mating.

Many of us can relate while emerging into public spaces, jittery and blinking, after 17 months of a dark and isolating pandemic.

The most fascinating (to me) but potentially disturbing (to

some people, understandably) experience I've had is observing a brain surgery, which I had the privilege of doing while I was a graduate student studying cognitive neuroscience. The patient had an arteriovenous malformation, a tangle of blood vessels that increases the risk of stroke. Before the surgeons removed it, they gently stimulated surrounding parts of the brain while the patient—who was awake—responded to questions that let them map the cortex and avoid resecting any parts involved in language. On page 70, neuroscientist and *Scientific American* advisory board member Christof Koch explains how such research has revealed the locations of surprising sensations throughout the brain.

Some bacteria, like cicadas, can also play the long game, as science writer Jennifer Frazer describes on page 76. While plesiosaurs drifted overhead 100 million years ago, cells settled to the bottom of the sea. When researchers pulled the microbes up in a seabed core and fed them, they woke up and started reproducing.

Svalbard is home to a global seed vault with [more than a million samples](#), a worst-case-scenario backup plan for preserving biodiversity. It's also the Arctic location of the world's fastest-warming town. On page 44, journalist Gloria Dickie takes us there and exposes the environmental, economic and social changes in a place where citizens of any of 46 countries are welcome to live.

Communities around the world are engaging in what amount to natural experiments in how to organize their economies and social contracts. On page 60, environmentalist and author Ashish Kothari discusses some of the principles of sustainability that have allowed these societies to flourish.

This year or possibly next, NASA is planning to launch a mission called DART—the Double Asteroid Redirection Test—that will be the first trial of a “kinetic impactor” strategy to deflect an asteroid. As science writer Sarah Scoles warns on page 36, it's just a matter of time before a very big asteroid threatens to slam into Earth. The sooner we can see it coming, the better chance we'll have of knocking it off course. Edgard Rivera-Valentín, a scientist who worked at the asteroid-observing Arecibo telescope before it collapsed recently, says, “Dinosaurs didn't have a space program. But we do.” 🌌

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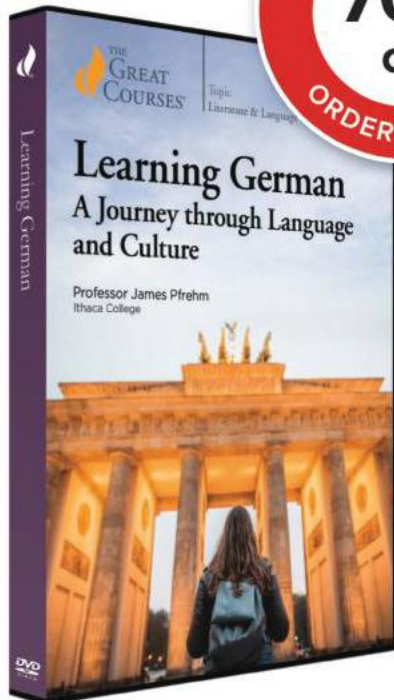
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7. Asking Questions and Numbers above 100
8. The Nominative and Accusative Cases and *kein-*
9. Time in German and Possessive Pronouns
10. Coordinating Conjunctions and *der-* Words
11. Modal Verbs and More Accusative
12. *Eine Reise nach München und Rothenburg ob der Tauber*
13. Present Perfect and *da-* and *wo-* Compounds
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15. Separable-Prefix Verbs
16. Subordinate and Infinitive Clauses
17. More Infinitive Clauses and the Dative Case
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19. Reflexive Verbs and Pronouns
20. More Dative and Subordinating Conjunctions
21. The Simple Past
22. *Bäuerin Bärbel und die rotbärtigen Zwerge*
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February 2021

UNIVERSE EXPANDER

“Cosmic Conundrum,” by Clara Moskowitz, describes how the most likely cause of the accelerating expansion of the universe is “vacuum energy,” the effect of virtual particles popping in and out of existence. But it does not explain why vacuum energy would cause the universe to expand. I would think that if space is filled with evanescent virtual particles, they would collectively exert a huge gravitational force that would counteract expansion.

CHRIS MARTINIAK *Berkeley, Calif.*

MOSKOWITZ REPLIES: Vacuum energy is positive and has a constant density throughout space. Thus, increasing the volume of space increases the total amount of vacuum energy, which requires work. It is the opposite of a gas, whose energy and density decrease as it expands. When that happens, the gas exerts positive pressure. In contrast, because vacuum energy is positive, it exerts negative pressure, so galaxies on the largest scales are pushed apart, not pulled together.

CONNECTING REALITIES

In “The Four Most Pressing Science Priorities for the Next President,” four articles focus on the need to address COVID, attention to evidence, climate change and the restoration of expertise. From a psychological point of view, all these topics are deeply intertwined, and the absence of that discus-

“Controlling COVID will end up being a challenge to human collaboration in exactly the same way mitigating the climate problem will.”

ROBERT A. BERLEY *SEATTLE*

sion weakens the theme of the report. Controlling COVID will, for example, end up being a challenge to human collaboration in exactly the same way mitigating the climate problem will. Both involve our capacity to not only work together but accept unwanted trade-offs. These issues stem from our enormous distrust of experts and hidden feelings (shame, fear of manipulation, and so on), along with an inherent uncertainty about the nature of our various realities.

The problems your report identifies are important but require a much deeper theory. What would that discussion entail? To begin with, a lot of self-searching. Maybe there could be an edition of the magazine that starts from that stance.

ROBERT A. BERLEY *Seattle*

THE EDITORS REPLY: In September 2019 we published a special issue called Truth, Lies & Uncertainty. It explores such themes across disciplines and covers a range of neuroscience, psychology and social sciences.

BORN TO RUN

In “On the Basis of Testosterone,” Grace Huckins compassionately chronicles the fact that while male athletes who were born with a genetic predisposition for height, strength or aerobic endurance are welcome to compete, women who were born with a similar predisposition are subject to intense scrutiny of their chromosomes and hormone levels. As the article describes, unnecessary medical interventions are currently ordered for women with high testosterone who wish to take part in longer international track events.

As a simple solution to this hypocrisy, the regulators should add the word “intentional” to “performance enhancement” as they exert scrutiny. It is not intentional when a man is born with genes that will lead to height or strength. Neither is it intentional when a woman is born with XY chromosomes, for example. The Olympic creed, as

espoused by the modern games’ founder, is that the important thing “is not the winning but the taking part.” All athletes should have the equal right to take part.

RAYMOND STEFANI *Lake Forest, Calif.*

I have been an avid reader of *Scientific American* for nearly 65 years, and publishing my article “Ensuring the Longevity of Digital Documents” in your January 1995 issue was one of the high points of my career as a computer scientist.

While I have largely been uninterested in competitive sports, the issues Huckins so adeptly considers have conceptual and practical implications far beyond that area. And she does an excellent job of teasing out the scientific, social and philosophical questions that her subject raises.

The article reinforces my frequent observation that overturning the metaphorical rock representing any subject always reveals far more complexity, subtlety, depth and motivation for further exploration than we might expect. This, to me, is the wonder of science and of the intellectual curiosity that is one of the joys of life for those of us who are fortunate enough to experience it.

JEFF ROTHENBERG *via e-mail*

COVID CASUALTIES

“Controlling COVID,” by Tanya Lewis [“The Four Most Pressing Science Priorities for the Next President”], says, “COVID-19 ... has killed hundreds of thousands of people in the U.S.—the highest toll of any country.” Though true numerically, this phrase is misleading. Per Johns Hopkins University on February 1, the U.S. had 441,319 total deaths. But it ranked 10th among deaths per 100,000 people in each country’s population, with 134.89 deaths per 100,000. And among deaths per all reported cases, it was far down the list, with a rate of 1.7 percent.

As an example, while the U.K. had 106,367 deaths at that time, it had 159.98 deaths per 100,000 and a case-fatality rate

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of 2.8 percent. And Belgium, which had only 21,092 total deaths, had 184.66 deaths per 100,000 and a case-fatality rate of 3 percent. This does not minimize the damage that COVID-19 has done to the U.S. or how poorly our public health infrastructure has responded to this pandemic. But this country is not the worst in the world.

RICHARD FERENCE *Three Rivers, Mich.*

WILD WILD BEHEST

In "Arachnid Architects" [Advances], Rachel Nuwer reports on a study exploring how spiders' legs automatically move to build webs that was led by biologist Fritz Vollrath. She writes that the researchers "tested the rules [of this movement] by programming a simulated virtual spider, and Vollrath says *the next step is to build a physical spider robot*" (emphasis mine).

If somebody could let Vollrath know that robot spiders are a bad idea, I would appreciate it. I've seen enough horror movies to recognize that this will not end well.

DAN MAHER *via e-mail*

CLIMATE SOLIDARITY

Jordan Salama clearly expresses our constant concern, albeit almost panic, about the neglect of the planet in "Earth Is on Fire" [Forum; January 2021]. He is not Chicken Little. His words ring true, and, sadly, when the U.S. should have been leading this battle, we took a four-year hiatus from all responsibility. I am 76 years old. Salama's generation can rest assured that it is not alone. Many of us choose our candidates, our stores, our purchases and our habits based on "saving the world" from trash, pollution, erosion and neglect. We are with you.

BILL MAUK *via e-mail*

THE EDITORS REPLY: In April, Scientific American and other major news outlets in a worldwide network called Covering Climate Now signed on to a declaration to refer to the ramifications of climate change as a "climate emergency."

ERRATUM

"Reestablishing Reality," by Jen Schwartz ["The Four Most Pressing Science Priorities for the Next President"], should have described Alondra Nelson as a professor at the Institute for Advanced Study in Princeton, N.J., not at Princeton University.

Postpandemic Health Habits

Some practices we've picked up because of COVID deserve to stick around

By the Editors

When the COVID pandemic finally retreats, the world will be different. We will have lost millions of lives—a tragic disaster that will devastate families and communities for decades to come. Other changes, of a less catastrophic nature, may not be bad things. For example, we will have lost some traditional habits and gained new ones. Take the way we greet one another: In March 2020 handshakes and cheek kisses were abruptly put on the do-not-do list to slow the spread of the virus. Once we're given the all-clear to resume those behaviors, however, we might still be wise not to do so. Even if COVID dwindles to become a mostly seasonal illness like influenza, both potentially deadly afflictions will still be with us. Do we really want to go back to rubbing our germmy hands on one another or exchanging virus-laden kisses at close quarters? Not if we're wise.

Greetings are just some of the deep-seated habits that have been cast in a new light by the year of COVID. The virus has taught us that we need a major culture change when it comes to basic public health hygiene. We learned, for example, that mask wearing is incredibly helpful in stopping the spread of all kinds of respiratory illnesses—something people in many Asian countries have known for years. Flu cases have been at record lows this year—the U.S. had at least 24,000 flu deaths during the 2019–2020 season, for instance, but so far about 450 this season. Although it is likely that many factors affected these rates, such as lockdowns, school closures and decreased travel, experts say masking has probably played a significant role. Now that most of us have impressive mask collections and lots of practice wearing them correctly, there is no excuse not to don one in public when you're under the weather. "It's considerate," says Angela Rasmussen, a virologist at the Georgetown Center for Global Health Science and Security. "I really hope that becomes part of our culture and that we are more conscious of how even mild infections can potentially impact other people."

Better yet, if you may be falling sick, stay home. In some cultures, notably in the U.S., going to work with cold or even flu symptoms can seem heroic—a stoic prioritizing of work over personal comfort. This now seems ridiculous. The pandemic has taught us to take community health more seriously and to recognize our personal responsibility to avoid sickening others. All workers who have the option of taking a sick day should do so when they need to, and all workplaces must focus on giving their employees this protection—for everyone's sake. The best move would be a federal law requiring employers to offer paid sick



leave. Right now almost 34 million people in the U.S. lack this benefit—that's nearly a quarter of civilian workers, according to the federal Bureau of Labor Statistics. And it is even scarcer among lower-paid workers. Predictably, people who are not paid when they call in sick are 1.5 times more likely to go to work with contagious illnesses, a 2010 study by the National Opinion Research Center at the University of Chicago found.

When companies expand their sick-leave policies, workplaces become healthier. A study carried out during the COVID crisis showed that when one company allowed more paid sick leave and encouraged employees to stay home when ill, more workers self-isolated when they got sick, and the company's offices avoided outbreaks. "This company did everything right, and it didn't have to close down," says Monica Gandhi, an infectious disease expert at the University of California, San Francisco, who co-authored the study. "Going to work when you're sick is all too common—especially among doctors, by the way. We need to encourage a culture to stay home when you don't feel well."

People are also much more likely to send their sick kids to school—triggering outbreaks of diseases that come home from class and infect parents—when they can't take paid time off from their job to care for them. We need employers to extend paid sick leave to include time to take care of ill family members, and we also need government support for backup child care, such as nannies who can come to a home to watch sick children if their parents must be at work.

If we do nothing else, we can at least keep up our improved handwashing habits this year. 🍷

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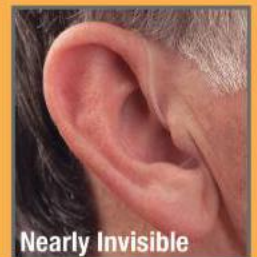
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Targeting Asian-American Scientists for Espionage Is Cruel and Unfair

Reckless indictments have stifled international collaboration, drained intellectual capital and violated the civil rights of U.S. citizens

By Alicia Lai

When trying to catch spies, it is tempting to cast a broad net despite the risk of making false accusations. Recently the U.S. Department of Justice has done just that. In an effort to crack down on what it depicts as an intellectual espionage campaign by China, it has revved up its prosecution of Asian-American citizens for scientific espionage and intellectual-property theft—from the notable case of Wen Ho Lee of Los Alamos National Laboratory in 1999 to Gang Chen of the Massachusetts Institute of Technology this past January.

The cycle is familiar yet somehow shocking every time: Immigrant or naturalized scientists are accused of disloyalty. Many are preemptively imprisoned and stripped of professional positions. Accusations of espionage are often found to be erroneous and ungrounded in science and are then dropped. Targeted scientists have raised plausible claims of racial profiling under the Fourth and Fourteenth Amendments, and at least one such case is currently pending in federal court.

What is driving this harsh crackdown? One answer is high economic stakes. Intellectual capital sits at the heart of the U.S. economy: an analysis of data from 2014 showed that industries relying on intellectual property directly accounted for 28 million jobs and \$6.6 trillion in value. Unsurprisingly, the U.S. reacts aggressively to foreign threats to its source of wealth. And there have been real threats tied to the Chinese government—for instance, inducements offered by the Thousand Talents recruitment program, the Equifax data breach of consumers' personal information and the SolarWinds hack of U.S. government data. Because of long-standing concerns, the Obama administration heightened penalties under the Economic Espionage Act. The Trump administration began the China Initiative to fight what it portrayed as an epidemic of intellectual theft. The Biden administration has already made high-profile arrests. Politicians on both sides of the aisle struggle to avoid

appearing “weak on China.” It is a persuasively simple narrative: stop foreign spies from stealing America's intellectual property.

But there is more to it. Too often prosecutions are mistargeted, and rhetoric ignores clear exculpatory evidence, capitalizing on the perception of Asian-Americans as perpetual foreigners. The sentiment can be traced back to the 1790 Naturalization Act (forbidding Asians and other nonwhite individuals from holding U.S. citizenship) and the 1882 Chinese Exclusion Act (essentially prohibiting all Chinese immigration, initially for 10 years and later indefinitely). And it extends to the current wave of anti-Asian crimes tied to the COVID-19 pandemic. Whereas overall hate crimes in the U.S. decreased by 7 percent during 2020, anti-Asian hate crimes increased by 149 percent. Recent news cycles are studied with violence: a two-year-old toddler stabbed in a Texas wholesale store, a woman doused with acid on her front porch in Brooklyn, a man knifed in Manhattan's Chinatown, a couple beaten with a rock in a sock in Seattle, a mother and her eight-year-old daughter stabbed to death while asleep in their California home, six women gunned down in a mass shooting in Atlanta.

Although China presents a legitimate national security concern—and genuine instances of espionage should be prosecuted—there is evidence that the U.S. is haphazardly conflating nationality with ethnicity. Representative Ted Lieu of California states that erroneous espionage prosecutions are “the latest example of our government's unfortunate inability to distinguish between American citizens and foreign adversaries.” One study found that the proportion of defendants charged under the Economic Espionage Act who were Chinese or Chinese-American rose from 17 to 52 percent between 2009 and 2015. More crucial is the rate of false positives: defendants of Chinese ethnicity have been unjustly accused at twice the rate of non-Chinese defendants. Many of these false positives—cases where the defendant is acquitted at trial, prosecutors drop all charges before trial, or the defendant pleads guilty to minor offenses and receives only probation—could be prevented by carefully examining the evidence before bringing charges, consulting a scientific expert on the merits, and avoiding biased, conclusory rhetoric.

The side effects of such a crude policy do more harm than good. Having spent my childhood in an idyllic Pennsylvania university town, I witnessed firsthand the community's reaction when a family friend—a Chinese-American physics professor who was a U.S. citizen—was erroneously accused, arrested and hustled away at gunpoint. Months later the Justice Department realized it had entirely misinterpreted the situation: it had accused him of sending schematics for sophisticated “pocket heater” technology to a colleague in China, but experts later clarified that the confiscated blueprints did not depict a pocket heater at all. The charges were dropped. But the professional, financial and reputational damage was done. The Asian-American community at the university buzzed with apprehension, fearing that no one was safe from unfounded accusations.

The current approach sweeps broadly and baselessly. Not only do rash prosecutions subject U.S. citizens to potential civil rights violations, but this climate causes a “brain drain” of intellectual



Alicia Lai is a Salzburg Cutler Fellow and J.D. candidate at the University of Pennsylvania Carey Law School, where she serves as articles editor for the *University of Pennsylvania Law Review*.



capital. According to the World Intellectual Property Organization, immigrants make up a significant proportion of U.S.-based inventors and have won a third of the Nobel Prizes given to Americans. But now many immigrant scientists and inventors are choosing to leave the U.S. for other countries on the promise of higher pay, prestigious positions, looser regulatory schemes and—most notably—no federal prosecutions for legitimate research activity. Brian Sun, a renowned litigator who successfully represented Lee in his civil lawsuit, explains: “If you’re criminally prosecuted and disgraced in this way ... it’s an academic death penalty: What are you left to do but go back to China?”

The long-term effect is rather perverse. As Princeton University molecular biologist Yibin Kang notes, “What’s happening is doing a great service for the Chinese government. If you turn this into a toxic environment, you’re actually helping the Chinese government to then recruit back to China.”

The U.S. loses in this situation any way you look at it. The country stifles its own innovation ecosystem by discouraging international partnerships, obstructing access to nonclassified federally funded research, renouncing immigrant intellectual capital and rejecting investments in innovations from certain other countries. On the international stage, it compromises its diplomatic standing by failing to recognize the diverse legal needs

of other countries and forcing the harmonization of patent law.

But these harms have gone largely unrecognized. In 2018 the National Institutes of Health—the main source of funding for many academic labs—instructed around 10,000 U.S. research institutions to continue cracking down. Sun calls these “gotcha” cases: they apply disproportionately heavy criminal penalties for mere administrative missteps. Several institutions, such as Emory University in Atlanta and MD Anderson Cancer Center in Houston, subsequently fired a number of their Asian-American researchers.

The myopia is astounding. Tensions and violence are escalating every day in courtrooms and on city streets. But at least in the scientific community, prosecutors, legislators, agencies and directors of research institutions have the power to slow down and consider the hard facts of each case. Jumping to conclusory prosecutions and terminations does no good for anyone.

By treating Asian-American citizens as perpetual foreigners and prosecuting them without merit or nuance, the U.S. will continue down a self-destructive path, harming its own citizens, innovation and economy. **SM**

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ADVANCES



Fossilized jumbles of dinosaur bones (like this one, at a site on the border of Utah and Colorado) present challenges for paleontologists reconstructing individual animals.

- De-ratting Rat Island brings about ecosystem recovery
- Scientists grow a lab model for bone
- Radioactive particles are measured in minuscule concentrations
- Fascinating fungi make up a 1900s bag



PALEONTOLOGY

Prehistoric Puzzle

A new process helps unscramble chaotic dinosaur deposits

The Intermountain West is positively littered with dinosaur boneyards. In Late Jurassic rock layers from New Mexico to Montana, paleontologists have uncovered deposits that look like skeletal logjams.

Whether connected or jumbled in a pile, the bones of prehistoric icons such as *Allosaurus*, *Stegosaurus*, *Diplodocus*, and more are often found in abundance—the result of Jurassic monsoon floods that washed multiple individuals and species together into great heaps, covering them with sediment that let them petrify. What might seem like a scientific bonanza, however, can quickly turn into an *Apatosaurus*-sized headache for experts trying to unscramble the details of prehistory from these osteological accumulations.

“How many dinosaurs are we looking at?” might seem like a simple question, but paleontologists know differently. Every [dinosaur skeleton](#), large or small, comprises 200 or more bones. As the Late Jurassic bonebeds formed, those skeletons did not always stay connected (“articulated”) or close together (“associated”). Decay, scavengers and the force of the sediment-carrying floodwaters fragmented and scattered the remains. In places such as central Utah’s Cleveland-Lloyd Dinosaur Quarry, there are

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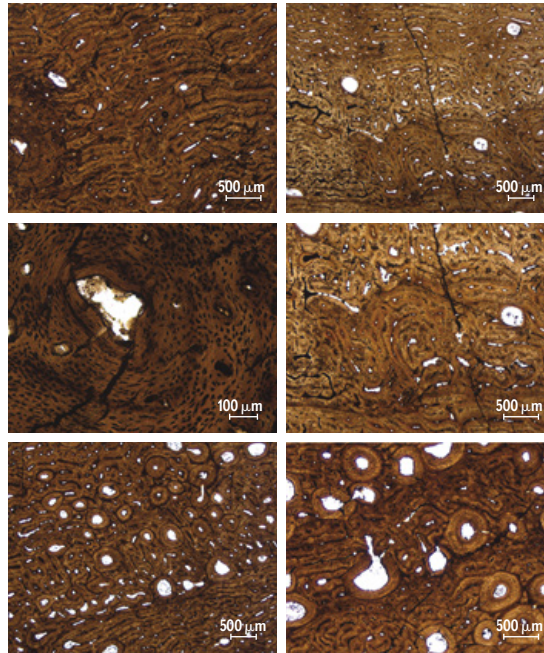
no complete articulated skeletons. Paleontologists estimate the site holds the remains of at least 46 *Allosaurus*—only because they have identified 46 left femora, or thigh bones, from this species there.

Such estimates are only minimums, however, as some animals' left femora are likely missing. A similar situation holds true for other prehistoric bonebeds, too. "Up until now, the main assignment of bones to an individual was made based on whether the bones were found articulated or associated," says University of Bonn graduate student Kayleigh Wiersma-Weyand. Paleontologists typically assume nearby bones of the same species and of comparable size belong to the same animal, but there has been no effective way to test this idea. Now Wiersma-Weyand and her colleagues offer a solution, published in *Palaeontologia Electronica*: look inside the bones.

Wyoming's Howe-Stephens and Howe Scott Quarries have long been hotspots for paleontologists. But like other famously productive Jurassic bonebeds in the West, the remains in these rocks were strewn together prior to burial. By examining the bones' microscopic cellular structure, however, the researchers were able to match isolated bones to identified individuals.

Team members thinly sliced core samples of long-necked sauropods' limb bones to examine under the microscope. (Bones' overall structure can be preserved after this sampling process, if done carefully.) Their study is the first to combine several types of microstructure analysis to narrow down which bones go with which skeleton. The technique involves examining features such as growth lines, the number of openings for blood vessels in bone tissue, and circular structures where new tissue has grown to replace old.

"I think this is a clever approach to a common problem," says Adelphi University paleontologist Michael D'Emic, who was not involved in the new study. It can be difficult, especially in historical collections made decades ago, to tell whether a particular bone matches others found



at the same site or was buried as an isolated piece. Some dinosaur skeletons displayed in museums have been reconstructed from multiple isolated bones from the same spot, without a way to check if all those parts belonged to one animal or several. "This paper opens up a new approach to determining which individual is which," D'Emic says—provided museums allow the necessary bone sampling.

The new study builds on decades of research into how a dinosaur's bones record its growth and life. That research focused on diverse bones from many locations, Wiersma-Weyand says, "but now we can apply our general insights to specific deposits."

In the case of a sauropod nicknamed "Max," for example, nearly all the bones were found in a disarticulated pile. Two of the lower leg bones were still together—but did the other isolated bones belong to this *Galeamopus*? The researchers found that structural details in the articulated bones matched those in many of the disarticulated ones, suggesting they belonged to the same individual. But the scientists also discovered that some bones, previously assigned to Max based on their appearance alone, actually belonged to other animals. Thus, they narrowed down Max's

Microscopic views of structures in the femur of an *Apatosaurus* nicknamed "Jacques," including vascular canals and signs of newer bone growth.

precise skeleton more than 148 million years after the dinosaur's death.

The study does have some limitations. "Different elements of a [single] skeleton have different biomechanical constraints and preserve slightly different biomechanical profiles," says Museums of Western Colorado paleontologist Julia McHugh, who was not involved in the new research. While acknowledging this, Wiersma-Weyand notes that her team's process is sometimes more powerful in determining which bones do *not* go together. Starting with bones that are still articulated or associated helps to set a baseline for attributing additional bones. The multiple lines of microscopic analysis work best to test a hypothesis about whether bones belong to the same animal.

Using microscopic structure to identify which bones belong to which dinosaurs has applications beyond better estimating how many individuals are in a deposit, McHugh says—and perhaps beyond dinosaurs, too. "This could be very useful for determining age profiles of populations in individual bonebeds," whether they are Jurassic dinosaurs or fossil mammals, she says.

This approach can also help reveal how these remains came to be where they are, Wiersma-Weyand says. In a petrified river channel, for instance, matching bones to specific dinosaurs can help paleontologists identify the direction the water was flowing when the bones were buried. This is key for reconstructing how bonebeds formed and for determining whether they record one burial incident or many.

"It's pretty exciting!" says University of Wisconsin-Oshkosh paleontologist Joseph Peterson, who was not involved with the study. "Being able to reconstruct how multiple skeletons disarticulated in conjunction with the environment they are buried in would bring aspects of modern forensic and crime-scene analysis to paleontology."

—Riley Black

SUSTAINABILITY

Ratted Out

Getting rid of terrestrial invaders benefits marine populations, too

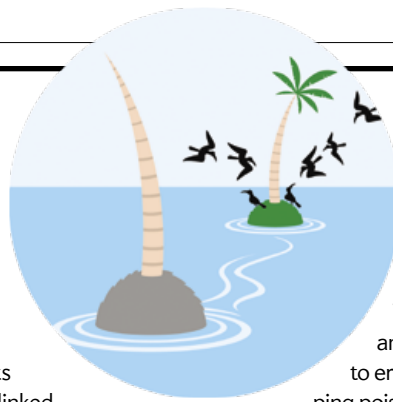
When Carolyn Kurle first visited Alaska's Hawadax Island, then known as Rat Island, she immediately noticed the silence. "When you're on an island that's never had rats, it's just like birds everywhere—it's really loud," she says. "So when you get to an island that does have rats, you really notice because it's cacophony versus quiet."

Nowadays Hawadax is once again a noisy place. Roughly a decade after a successful effort to rid the island of its predatory rodents, a bounty of seabirds has returned. And the benefits have extended across the island's entire seashore ecosystem, which again teems with diverse life. These findings, published in *Scientific Reports*, show that certain ecosystems can recover with surprising speed if given the chance.

"This study is an example of something positive that can happen when we humans

take action to clean up after ourselves," says Kurle, who is lead author of the study and a conservation ecologist at the University of California, San Diego. "It also highlights how everything is interlinked, especially in coastal systems."

Kurle originally began studying rats' ecological effects on the remote Aleutian archipelago for her doctoral research. The voracious rodents colonized Hawadax after a Japanese shipwreck in the 1780s, and they quickly wiped out seabird communities. Kurle's first findings, published in 2008, showed that the rats affected not just birds but the entire food chain—all the way down to algae. Without birds to eat seashore invertebrates, populations of snails, limpets and other herbivorous species exploded and gobbled up much of the marine kelp, which provides crucial habitat for other organisms. "Certain invasive species can have impacts beyond those that are most



obvious," Kurle says.

Those early findings inspired the U.S. Fish and Wildlife Service, in partnership with The Nature Conservancy and Island Conservation, to eradicate the rats by dropping poison on Hawadax. Kurle

and her colleagues secured funding to survey the island five and 11 years after the intervention. They found that its intertidal ecosystem had steadily recovered and now resembles that of other Aleutian Islands that were never invaded by rats, with significantly fewer marine invertebrates and much more kelp cover.

"Very few rat-eradication projects have focused on the impact on marine ecosystems, so the Hawadax Island case is really noteworthy," says University of Tennessee, Knoxville, ecologist Daniel Simberloff, who was not involved in the study. "This is a very cool, elegant result from an academic ecology standpoint and, of course, is important in terms of conservation." —Rachel Nuwer

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BIOLOGY

Deep Strangers

Newfound ocean bacteria slip past human immune sensors

Our immune system must recognize a microbe as potentially dangerous before it can react to it as a threat. To help do so, cells use special pattern-recognition receptors that broadly identify classes of microbes based on certain molecular structures.

One of these signature structures is lipopolysaccharide (LPS), a long chain of sugars anchored to the cell membranes of numerous bacteria types. Many researchers assumed our bodies could recognize a version of LPS produced by any microbe, except

meters (nearly two miles) below the ocean's surface. They cultured 50 strains in an on-board laboratory and exposed each one to human and mouse immune cells in a dish. The immune cells recognized the LPS on a few of the new bacterial strains and reacted the way they would to ubiquitous bacteria such as *Escherichia coli*. But 80 percent of the deep-sea bacterial strains were completely unrecognizable to one or both of two LPS-detecting pattern-recognition receptors.

Boston Children's Hospital immunologist Jonathan Kagan, a study co-author. But it apparently does not detect at least some microbes that live in an environment we would never naturally encounter.

Does this mean we need to worry about deep-sea microbes overrunning our immune systems? Probably not. For one thing, bacteria that thrive in the cold, dark saltiness of the deep ocean are unlikely to do so inside our warm bodies. And the immune system has many other mechanisms for sensing invasive bacteria.

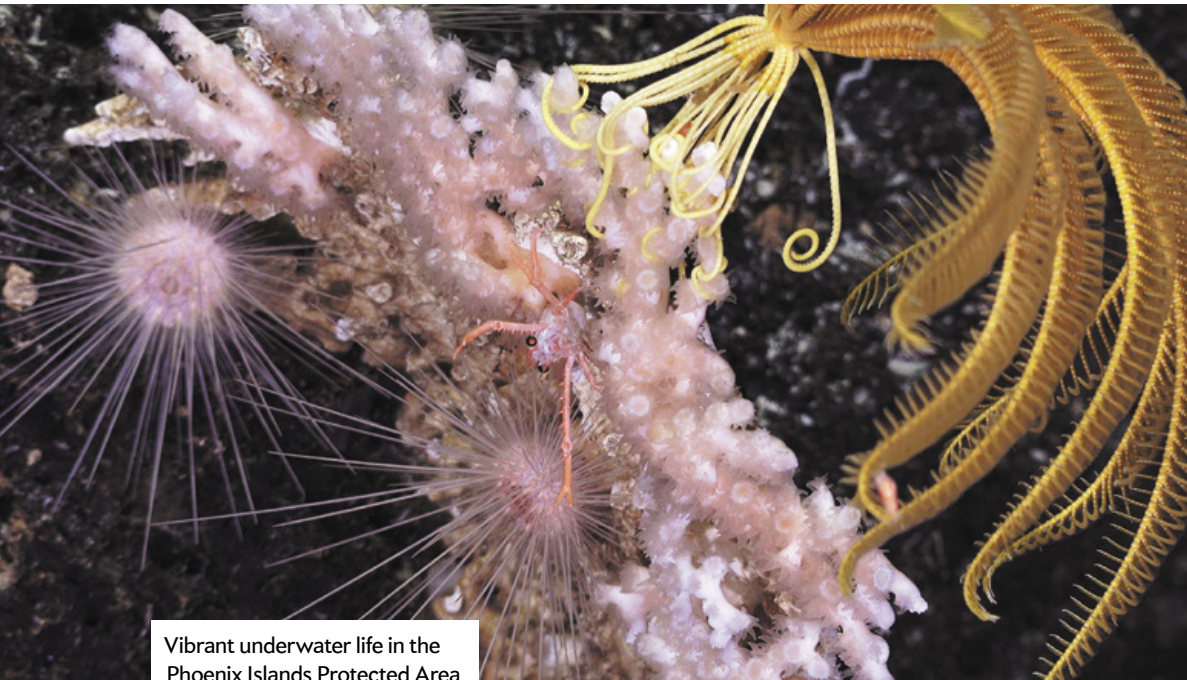
Nevertheless, this study could lead to interesting clinical applications. Researchers have long considered including LPS in vaccines to help kick-start the immune system—but it causes such a strong immune

response that this can be dangerous. Although most of the Phoenix Islands' deep-sea bacteria had LPS varieties that triggered no response, some provoked a moderate one. Kagan says these new LPS molecules might potentially be used as a "dial" to let cancer vaccine researchers fine-tune immune responses, instead of just flipping a switch between zero and 10.

The deep ocean is not a traditional place for immunology research. This study emerged from a unique collaboration between Kagan, lab member Anna Gauthier and

marine ecologist Randi Rotjan, who is co-chief scientist of PIPA. Rotjan had planned an exploratory expedition, and she invited Gauthier to collect and characterize deep-sea bacteria along the way.

The researchers are planning another cross-disciplinary expedition to PIPA next summer to investigate more targeted questions, including how native deep-sea organisms such as corals respond to their bacterial neighbors, Rotjan says. But the team is open to surprises, she adds: "That's the beauty of basic research—you never know where it's going to go." —Stephanie Melchor



Vibrant underwater life in the Phoenix Islands Protected Area

those of a few pathogens that specifically evolved to evade immune detection. But a new study reveals there are strains of deep-sea bacteria whose LPS is essentially invisible to our cells' pattern-recognition receptors.

In 2017 a team of scientists set sail on the Schmidt Ocean Institute's research vessel *Falkor* for the Phoenix Islands Protected Area (PIPA) in Kiribati, one of the planet's largest marine conservation zones, located in the central Pacific Ocean. As part of their exploration of the largely untouched ecosystem, the researchers collected bacteria from as deep as 3,000

"I think the paper is super exciting," says University of Pennsylvania immunologist Sunny Shin, who was not involved in the study. She notes that the findings go against the prevalent understanding that these receptors can recognize any foreign microbe. Instead the research, published in *Science Immunology*, suggests that pattern-recognition receptors have evolved to reliably detect only microbes found in familiar environments.

"Our immune system certainly has a need to detect every microbe that we would see as we go to Starbucks," says

IN THE NEWS

Quick Hits

By Sarah Lewin Frasier

U.S.

Analysis of radar records revealed that at their height more than 45 million grasshoppers—30.2 metric tons—swarmed Las Vegas one 2019 summer night. Artificial light and an unusually moist spring likely caused the onslaught.

MEXICO

An ancient “eagle shark” fossil, discovered in Nuevo León, has long, thin fins that stretch about 1.9 meters—farther than its 1.65-meter body length. A new study suggests the shark lived 93 million years ago and filled a filter-feeding niche that is held by manta rays today.

NORWAY

Researchers at last identified the origin of translucent spheres, up to a meter wide, found by divers off western Norway: the almost featureless blobs each carry hundreds of thousands of squid eggs in mucus. Samples from the spheres revealed embryos of the species *Ilex coindetii* at different stages of development.

RUSSIA

Underneath Siberia's Lake Baikal, Earth's deepest lake, a large new neutrino-detecting telescope has joined the quest to measure these almost massless subatomic particles. The freshwater and ice deflect cosmic rays but let through neutrinos—and maybe dark matter and other exotic particles—to hit the telescope's detectors.

JAPAN

Cherry blossom season's peak this year came at its earliest yet, according to records stretching back to A.D. 812. The previous earliest peak occurred one day later than this year's, in March of 1409. Japan's detailed records of such events help scientists track changing climate conditions.

RWANDA

Young mountain gorillas that lose their mothers fare just as well as their peers that do not, according to 53 years of data from the Gorilla Fund's Karisoke Research Center. The social group apparently helps raise the young apes, avoiding ill effects seen in many primates and other social animals.

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MEDICINE

Skeleton Key

A new process builds living bone models for research

Laboratory-grown organoids—tiny cellular structures that mimic an organ’s anatomy and functions—are becoming increasingly useful in medical research. Such micro-models of the [brain](#), [lungs](#) and other organs have been around for years, but creating them for bone tissue has proved uniquely difficult. Bone stands apart because its different cell types exist within an extracellular matrix, a continuously remodeled network of collagen and minerals. Previous organoid attempts have failed to capture how human bone cells form in parallel with this matrix and interact with it. Now, however, researchers say they have developed a lifelike model that will help them better understand a range of challenging bone diseases.

A new study in *Advanced Functional Materials* presents the first organoid with a “unified view” of bone formation’s critical early stages, according to lead author Anat Akiva, a cell biologist at Radboud University Medical Center in the Netherlands. Akiva and her colleagues found that by applying mechanical force to mimic the stresses that shape bones in the human body, they could trigger bone marrow stem cells to transform into bone-building osteoblasts and growth-regulating osteocytes, which together produce all the

proteins they need to function. The researchers’ process also spurred growth of an extracellular matrix closely resembling that of human bone tissue. The end product after four weeks of growth: a miniature cylinder of woven bone, which in living bodies is the type of bone laid down first and later replaced with a more mature form.

Researchers could use this new tool to watch what happens at the molecular level when the building process goes wrong, causing bone disorders that affect tens of millions of people worldwide.

One such disorder is osteogenesis imperfecta, or “brittle bone disease,” a genetic condition that weakens the extracellular matrix and can cause hundreds of spontaneous bone fractures over a person’s lifetime. Bone cancers such as osteosarcoma also involve dysfunctional bone formation, and this model could explore how cancer cells infiltrate the extracellular matrix and make unwanted new bone.

Bone organoids could additionally help doctors develop highly personalized therapies, says Ralph Müller, deputy director of the Institute for Biomechanics at ETH Zürich, who was not involved in the study. To craft a treatment plan, investigators could grow organoids from patients’ living tissue samples and test how an individual’s bones would respond to various interventions.

“We have a reliable system for forming bone,” Akiva says. “We can actually go to the fine details to study what exactly goes wrong and if and how we can fix it.”

—Anna Goshua



COGNITIVE SCIENCE

Brain Training

Older adults boost memory through virtual reality

Scientists have long sought to prevent sharp memories from dulling with age, but the problem remains stubborn. Now research published in *Scientific Reports* suggests [virtual reality](#) might help older people recall facts and events based on specific details.

The study involved 42 healthy older adults from the San Francisco Bay Area. Half spent a dozen hours over four weeks playing a virtual-reality game called Labyrinth; they strapped on headsets and walked in place, roaming virtual neighborhoods while completing errands. The other half, in the control group, used electronic tablets to play games that did not require navigating or recalling details. After 15 sessions, the latter performed roughly the

same as before on a long-term memory test based on picking out objects they had seen about an hour earlier. But the Labyrinth players’ scores rose, and they were less frequently tricked by objects that resembled ones they had viewed.

Those improvements “brought them back up to the level of another group of younger adults who did the same memory tests,” says cognitive neuroscientist Peter Wais of the University of California, San Francisco. He and his colleagues designed the VR game, which they say likely stimulates the hippocampus—a brain area important for long-term memory. The team did not observe improvement on two other tests, which measured autobiographical memory and spatial memory capability.

“What they’re trying to do is uniquely suited to VR,” says Meredith Thompson, a Massachusetts Institute of Technology education researcher, who studies learning through VR games but was not involved in the new study. VR can provide greater immersion and engagement than other games, she says, adding that after this proof-of-concept study, “it would be great

to actually follow people over time and see what this type of game does for long-term memory.” Wais’s team is now investigating how long the observed effects last and which elements of the training have the most impact.

“It’s great that they measured expectations for improvement for the intervention and placebo conditions,” says Daniel Simons, a University of Illinois at Urbana-Champaign cognitive psychologist, who was also not involved in the study. Experiments with other games that claim to train the brain have often failed to evaluate this, he notes. But Simons adds that testing three measures, instead of just one, increased the likelihood of finding an improvement. And it remains unclear how test performance in a laboratory setting might translate to real-world situations. The outcome, Simons notes, “needs to be repeated, ideally with a much larger group, before it’s treated as a strong finding.”

For now, Wais says, the team hopes its studies with similar-sized groups will help draw funding to test the game in a larger pool of participants.

—Carolyn Wilke

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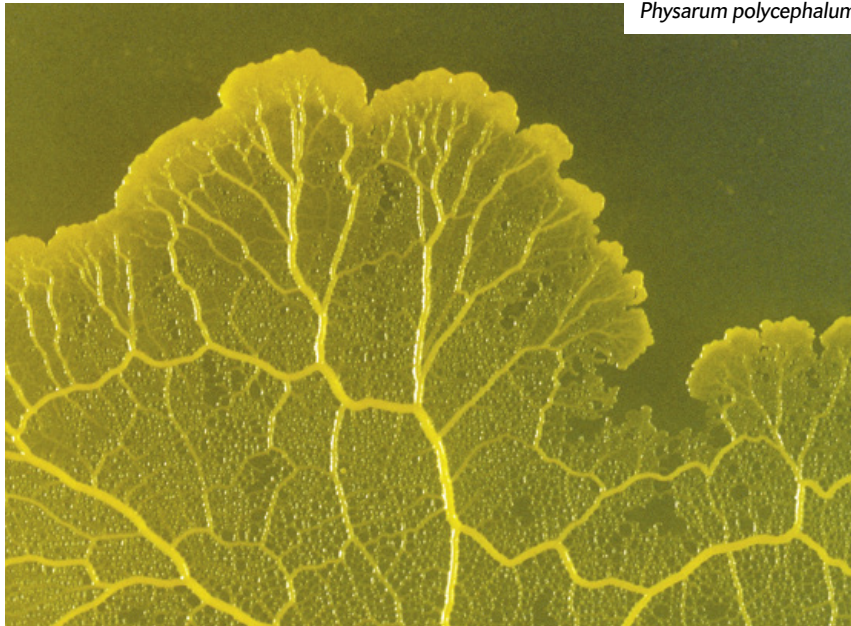
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Physarum polycephalum



BIOLOGY

Slime Memory

Simple slime molds “remember” food sources

Like all slime molds, *Physarum polycephalum* has no brain or nervous system—yet it somehow “remembers” food sites for future reference. In a new paper, biophysicists Mirna Kramar and Karen Alim of the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany, describe how the organism’s internal structure changes to encode past food locations.

Although slime molds are extremely simple organisms—just a system of interlaced tubes—they can solve complex optimization problems such as finding the shortest path through a maze. Pure stimulus-response activity patterns—for instance, crawling toward increasing concentrations of certain molecules or avoiding harmful mechanical stimuli—cannot explain the extent of their skill. How they can take in and retain information has long remained unclear.

The study, published in the Proceedings of the National Academy of Sciences USA, revealed that when parts of *P. polycephalum* come in contact with a food source, they release a substance that softens the tube network’s gel-like walls, making them widen from their inherent internal pressure. The slime mold moves by expanding

along wider tubes and pruning narrower ones—so the enlarged tubes effectively record past food locations, as they influence the organism’s overall direction of growth even after the food is gone.

The researchers do not yet know what the softening substance is, but by modeling changes in tube diameters, they found it is likely a soluble material that spreads by flow and diffusion. The team suggests this mechanism could also be common in other “living flow networks,” such as vertebrate vascular systems.

Kramar and Alim “have pinned down nicely a mechanobiological mechanism for slime mold behavior implementing something like memory,” says University of Bremen physicist Hans-Günther Döbereiner, who was not involved in the study. Future research into a slime mold’s ability to carry out complex tasks, he says, will require an examination of “molecular signaling, material properties and flow patterns of the cellular fluid regulating its behavior.”

New Jersey Institute of Technology biologist Simon Garnier, who was also not involved in the study, adds that this work builds on prior investigations of how this organism encodes past experiences. The researchers’ model “provides a nice mechanistic explanation for how slime mold achieves this feat,” he says. It could lead to improved network optimization and routing algorithms, Garnier adds, similar to those inspired by ant colonies.

—Lars Fischer

PHYSICS

The Tiniest Trace

A new impurity-finding process could aid the search for dark matter

A concentration of one part per billion is like a pinch of salt in 10 tons of potato chips—and scientists can now find radioactive particles at concentrations millions of times smaller. In the *Journal of Analytical Atomic Spectrometry*, researchers describe successfully detecting radioactive uranium and thorium hiding among something like a million billion other atoms.

The ability to spot these tiny amounts of radioactive elements, which occur naturally in metals such as gold that are often used in laboratory instruments, could have big consequences for particle physics. Radioactive traces limit sensitivity in detectors searching for exotic particles, including those that might make up dark matter; a minuscule radioactive impurity inside a detector can be mistaken for a particle's signature, throwing off the entire experiment.

"Before we do anything else, we need the cleanest possible materials," says Michelle Dolinski, a particle physicist at Drexel University and the Enriched Xenon Observatory, who was not involved with the study. Her



A mixing chamber for the Super Cryogenic Dark Matter Search

work on rare particle searches intertwines with that of chemists tracing radioactivity.

"Physics needs really push the chemistry," says Pacific Northwest National Laboratory (PNNL) chemist and study co-author Eric Hoppe. He and the other researchers pinpointed small concentrations of radioactive thorium and uranium in metallic samples by using a mass spectrometer, which separates particles based on their mass.

First, the scientists had to make radioactive elements more massive than a metal's other atoms, explains lead author Khadouja Harouaka, also a chemist at PNNL. To do so, they heated a metallic sample until it became very reactive and pushed it into a chamber full of oxygen.

Any thorium or uranium in the sample then combined with the oxygen to form molecules massive enough to stand out in spectrometer data. Scientists next counted these oxidized radioactive particles and calculated their original concentration—a value that suggests how much radiation the material would introduce to physics experiments.

Whereas many previously developed particle-detection methods must be modified for each specific metal, the new technique always uses the same heating and oxidizing steps. "The whole palette of materials is opening up," Hoppe says.

Material options are critical for the design of particle detectors, says Priscilla Cushman, a physicist at the University of Minnesota and the Super Cryogenic Dark Matter Search experiment, who was not involved with the study. "There are so many little pieces of [a dark matter] experiment that have different functions," she says. "The materials that are used for electrical or thermal connections, or even insulation, all those have to be radio pure." Every new metal examined can be considered for detector components. Hoppe is also looking ahead: "We're constantly trying to knock down all of the suspect [radioactive] materials. This work is a nice step forward."

—Karmela Padavic-Callaghan

PAUL BRINK, SUPERCDMS COLLABORATION, STANFORD UNIVERSITY AND SLAC NATIONAL ACCELERATOR LABORATORY

ENERGY

Lake Power

Methane from freshwater could provide renewable energy

In 1776 Italian physicist Alessandro Volta discovered something bubbling up among the reeds at the marshy end of a mountain lake. It turned out to be methane, a potent greenhouse gas produced by microbes living in the lake's sediments. According to the latest estimates, lakes and reservoirs account for 10 to 20 percent of global methane emissions, and scientists expect their contribution to rise because of climate change and nutrient runoff.

Methane is also a fuel, however—as Volta learned when he set it on fire. It is, in fact, the primary component of natural gas. And

a recent study in *Environmental Science & Technology* suggests methane in freshwater may represent an overlooked energy source.

The authors propose extracting some of the gas from lakebeds by separating it from water using a specialized membrane. Minerals called zeolites could then trap the methane molecules to be pumped to the surface. There are already membranes that can isolate methane from wastewater, and promising synthetic zeolites are under development, says Maciej Bartosiewicz, a biogeochemist at the Polish Academy of Sciences and lead author of the study. He envisions starting small, perhaps with mobile devices deployed in hydroelectric dam reservoirs (which often emit methane), to complement other green energy options.

Methane-rich water has been pumped from the depths of Rwanda's Lake Kivu to supply local electricity since 2015. But that

lake has exceptionally high levels of the gas, and some scientists are skeptical that it can—or should—be extracted in other settings. At lower concentrations, methane extraction is not yet cost-effective, and "the material and energy needed to harvest it are likely huge," says David Bastviken, an environmental scientist at Linköping University in Sweden, who was not involved in the study. Bastviken also worries about potential ecological consequences.

Bartosiewicz acknowledges these concerns, including possible effects on methane-eating microbes and the rest of the food chain. But he notes that human activities have already increased methane production in many ecosystems. So removing some gas might be okay in certain locations, he says, adding that he is eager to investigate solutions: "There needs to be a step forward."

—Julia Rosen

ANTHROPOLOGY

Fabric from Fungi

Researchers pinpoint mycelial source of museum artifacts

Biofabrication companies are increasingly excited about the prospect of using fungi to produce sturdy, sustainable alternatives to plastic and leather. But a new finding suggests that Indigenous Americans were already making “mycotextiles” at least a century ago. The study, published in *Mycologia*, confirmed the fungal origin of two wall pockets crafted by a Tlingit woman in Alaska in 1903. Some historical mycotextile use has also been reported in Europe, but “that I know of, this is the first documentation of the use of this material anywhere in North America,” says Nancy Turner, an ethnobotanist at the University of Victoria, who was not involved in the study.

Study co-author Deborah Tear Haynes learned of the artifacts while working as collections manager at Dartmouth College’s Hood Museum of Art. The original owner had labeled one of the pockets, found in the museum’s collection: “Pair of fungus bags. Wedding present from Indian neighbors.” Intrigued, Haynes spent years calling experts to confirm this identification—but none had heard of fungal textiles, and her inquiries attracted little interest. “I just couldn’t let go until I figured out what these things were made of,” she says.

Haynes finally made progress by taking

a closer look using Dartmouth’s electron scanning microscope facility. The images revealed mycelia—intertwined threadlike fungal structures that permeate soil or wood and can form thick mats that are strong, supple and durable. “You can’t rip it apart with your hands; it’s just like leather,” says study co-author Robert Blanchette, a forest pathologist at the University of Minnesota.

Comparing details of the mycelia with modern species descriptions, Blanchette determined that the bags were made from the agarikon fungus—a tree-decaying species that is now disappearing along with the old-growth forests of the western U.S. “This was a significant fungus for Indigenous people. It was used medicinally and spiritually all along the Pacific Northwest coast,” Blanchette says. According to one medical anthropologist, the Spokane people in Washington State used agarikon mats in cradleboards for diaper rash. Twentieth-century loggers described bandaging wounds with it, and the ancient Greeks used it to treat tuberculosis. Recent studies suggest agarikon extracts have antibacterial and antiviral properties, and they may even be effective in animals at [treating some cancers](#).

“There’s likely more evidence of the use of this material, and it may well be in museums and collections,” Turner says. No biofabrication companies currently use agarikon mycelial mats. But Blanchette says they can be cultured in a laboratory, making this rare species a viable option for modern mycotextile applications, too.

—Cypress Hansen



The fruiting body of an agarikon fungus

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ADVANCES

BOTANY

Science in Images

By Leslie Nemo

Anna Atkins, born in England in 1799, was perhaps an unlikely photography pioneer—she was an amateur botanist, one of a select set of hobbies then considered appropriate for a British lady. She collected and hand-drew samples of the myriad algae varieties found along Britain's coastlines. Her drawings were meticulous, but some specimens were so small and detailed that she had no choice but to experiment with a new high-tech documentation technique.

In the mid-1840s English astronomer and chemist John Herschel introduced Atkins to his new photography method. When he coated a piece of paper in iron salts and left it out in the sun, the light would turn the page blue—save for any portion covered by some object placed atop the paper. Herschel called the technique cyanotyping; it is better known today as blueprinting.

Atkins adopted this method to document her algae samples, carefully bending each of the organisms—which were becoming increasingly brittle from time out of the water—to fit on a single page so the chemicals and sun would form a lasting impression. She collected these images in a three-volume set called *Photographs of British Algae: Cyanotype Impressions*. Only around a dozen copies are known to still exist—and the first volume, released in October 1843, is widely considered the earliest book of photography ever published. Here's a glimpse at some of these cyanotyped algae:

- 1** *Chordaria flagelliformis*: Like many other species of brown seaweed, this alga contains fucoidan, a sugar that researchers have long investigated as an agent that might regulate the immune system or slow blood clotting.
- 2** *Cystoseira granulata*: This species and some of its closest relatives sprout into



dense aquatic forests along coasts. Fewer of these specimens now exist to be collected than when Atkins was around; biologists suspect that pollution, too much nutrient runoff and increasingly dirty water are killing off this genus of seaweed.

- 3** *Dictyota dichotoma*: Shown in its young state and in fruit. The *Dictyota* genus of brown seaweed has shown promise as a potential feed additive that might cut back on the greenhouse gas methane cows release through flatulence and burping.
- 4** *Alaria esculenta*: Otherwise known as badderlocks, dabberlocks or winged kelp, this ribbonlike alga variety is popular with seaweed farmers in Maine, where it was one of the first three species to be grown commercially in the U.S.

To see more, visit scientificamerican.com/science-in-images

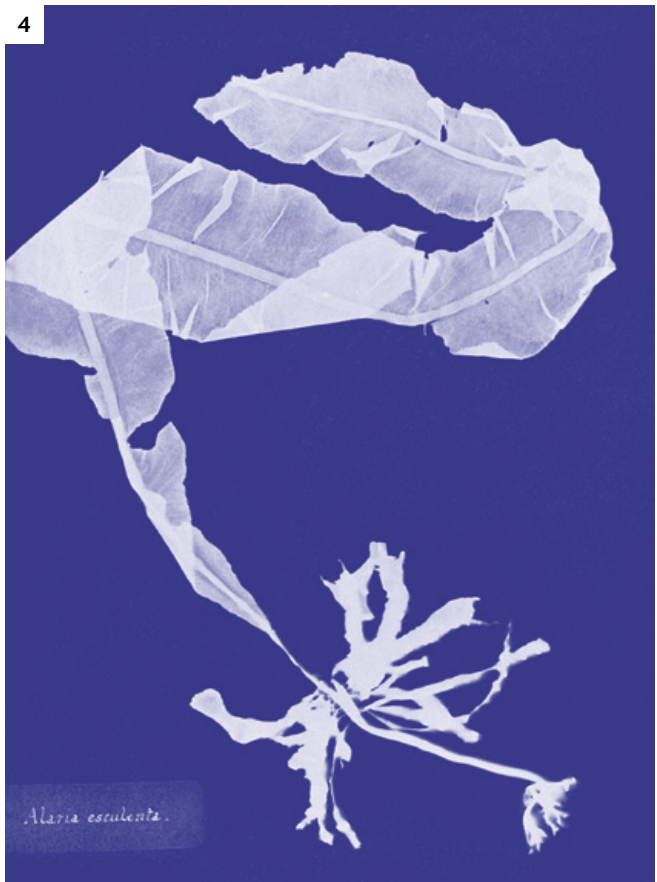
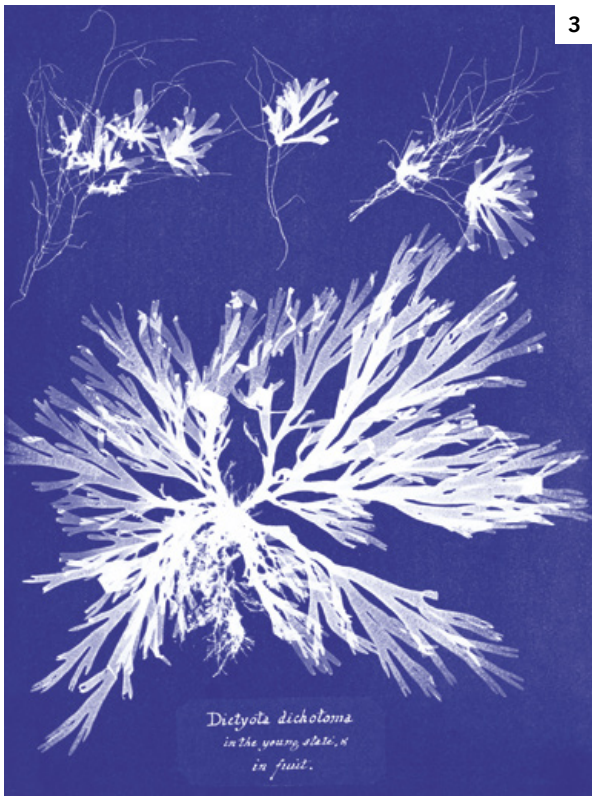


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Michael L. Johnson's seven books of poetry include *Sky Land: A Southwestern Cycle*. He has also written books and articles about artificial intelligence, expert systems, New Journalism, education and Western American history.



Turing and the Apple

Nothing's wholly certain. A half
apple lay beside the bed, bites
taken out of it, when his corpse
was found—though no one really tried
to ascertain if it contained
cyanide. After he had seen
Snow White, off and on he would chant
the haggish queen's vile couplet. Did
he dip the apple in the brew
and let the Sleeping Death seep through?
And did it make his dreams come true?
Was he the smartest in the land?
What determines when a machine
must stop? Why is a program bound
to crash? Or a person? Was some
forgetful prince supposed to drop
by, give him the reviving kiss,
and start the soap opera up
again, absent forced estrogen?
Or was his being too at odds
with everything the problem? What
went amiss in this fairy tale?
Was the steeped fruit Newton's or Eve's?
Did he conceive himself beyond
skin and bone? Did he want to be
quantum-mechanically reborn
in the new form of other flesh?
Foresee a castle in the sky
for happy-ever-aftering?
His life of paradox remains
a core enigma. There's no test
to disambiguate the dead
and sort out accident from will,
sheer inevitability
from Russian-roulette randomness,
much less a computer to plumb
the strange-looped onion depths of mind
and crack its tangled cryptograms.
We'd have the truth come absolute,
data bereft of *ifs*, but it's
adrift, mute, undecidable,
lost in the laptop cenotaph.





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*.

Instruments of Bias

There are ways to keep prejudice against race and gender out of medical devices

By Claudia Wallis

We don't think of everyday devices as biased against race or gender, but they can be. Electrical engineer and computer scientist [Achuta Kadambi](#) is familiar with the problem both professionally and personally. "Being fairly dark-skinned myself," Kadambi says, he sometimes cannot activate no-touch soap dispensers and faucets that detect light bouncing off skin. At one airport, he recalls, "I had to ask a lighter-skinned traveler to trigger a faucet for me."

Medical devices, too, can be biased—an issue that has gained attention during the COVID pandemic, along with many other inequities that affect health. In a recent article in *Science*, Kadambi, an assistant professor at the University of California, Los Angeles, Samueli School of Engineering, describes three ways that racial and gender bias can permeate medical devices and suggests a number of solutions. Fairness, he argues, should be a criterion for evaluating new technology, along with effectiveness.

The first problem, Kadambi says, is physical bias, which is inherent in the mechanics of the device. Then there is computational bias, which lies in the software or in the data sets used to develop the gadget. Finally, there is interpretation bias, which resides not in the machine but in its user. It occurs when clinicians apply unequal, race-based standards to the readouts from medical devices and tests—an [alarmingly common practice](#). "Bias is multidimensional," Kadambi says. "By understanding where it originates, we can better correct it."

Physical bias made news last December when a [study at the University of Michigan](#) found that pulse oximeters—which use light transmitted through skin and tissue to measure the oxygen in a person's blood—are three times more likely to miss low oxygen levels in Black patients than in white ones. Other instruments can have trouble with skin color, too. Remote plethysmography, a new technology that measures heart rates by analyzing live or recorded video, works less well for people of color when programmed to pick up blushlike changes in the skin. But, Kadambi says, "there are multiple ways to extract signals, with varying degrees of bias." A team at the Massachusetts Institute of Technology, for example, created a remote plethysmograph that [reads tiny changes in head motion](#) that occur when the heart beats. Kadambi's laboratory is trying other solutions, including analyzing video images with thermal wavelengths rather than visible light.

Computational biases can creep into medical technology when it is tested primarily on a homogeneous group of subjects—typically white males. For instance, an artificial-intelligence system used to analyze chest x-rays and identify 14 different lung and chest diseases worked less well for women when trained on large-




ly male scans, according to a [2020 analysis](#) by a team of scientists in Argentina. But training the system on a gender-balanced sample produced the best overall results, with no significant loss of accuracy for men. One reason, Kadambi suspects, may have to do with a concept called domain randomization—adding more variety to the training data tends to improve performance.

Stopping computational bias means making a much greater effort to recruit people from different populations to participate in the design and testing of medical devices. It would help if research teams were themselves more diverse, observes Rachel Hardeman, a public health scientist at the University of Minnesota, who studies reproductive health and racial equity. "When you have a history of distrust [of medical experiments], plus you don't see anyone who looks like you that's actually doing the work, it's one more signal that it's not for you," she says.


In addition to building diversity among researchers, Hardeman favors mandatory training of medical personnel in the fundamental ways in which racism impacts health, a step that might also help counter practices that lead to interpretation bias. California has moved in this direction, she notes, with a 2020 law requiring health-care providers treating pregnant women and their newborns to complete a [curriculum](#) (one Hardeman is designing) aimed at closing racial gaps in maternal and infant mortality.

For engineers to get the overall message, Kadambi proposes another mandate: include a "fairness statement" in published work on any new medical device that indicates how well it performs across different populations. Journals and engineering conferences could require that information just as they require conflict-of-interest statements. "If we add a metric that incentivizes fairness, who knows what new ideas will evolve?" Kadambi suggests. "We may invent radically different ways of solving engineering problems." ■



INFECTIOUS DISEASE

Deadly Ki



FUNGUS *Candida auris* lurks in hospitals, where it infects patients with impaired immune systems.

Kingdom

Killers of 1.6 million people every year, fungi are emerging as some of the most lethal microbes on the planet—and we don't really know how to stop them

By Maryn McKenna

Maryn McKenna is a journalist specializing in public health, global health and food policy and a senior fellow at the Center for the Study of Human Health at Emory University. She is author most recently of *Big Chicken: The Incredible Story of How Antibiotics Created Modern Agriculture and Changed the Way the World Eats* (National Geographic Books, 2017).



IT WAS THE FOURTH WEEK OF JUNE IN 2020, AND THE MIDDLE OF THE SECOND WAVE OF THE COVID pandemic in the U.S. Cases had passed 2.4 million; deaths from the novel coronavirus were closing in on 125,000. In his home office in Atlanta, Tom Chiller looked up from his e-mails and scrubbed his hands over his face and shaved head.

Chiller is a physician and an epidemiologist and, in normal times, a branch chief at the U.S. Centers for Disease Control and Prevention, in charge of the section that monitors health threats from fungi such as molds and yeasts. He had put that specialty aside in March when the U.S. began to recognize the size of the threat from the new virus, when New York City went into lockdown and the CDC told almost all of its thousands of employees to work from home. Ever since, Chiller had been part of the public health agency's frustrating, stymied effort against COVID. Its employees had been working with state health departments, keeping tabs on reports of cases and deaths and what jurisdictions needed to do to stay safe.

Shrugging off exhaustion, Chiller focused on his in-box again. Buried in it was a bulletin forwarded by one of his staff that made him sit up and grit his teeth. Hospitals near Los Angeles that were handling an onslaught of COVID were reporting a new problem: Some of their patients had developed additional infections, with a fungus called *Candida auris*. The state had gone on high alert.

Chiller knew all about *C. auris*—possibly more about it than anyone else in the U.S. Almost exactly four years earlier he and the CDC had sent an urgent bulletin to hospitals, telling them to be on the lookout. The fungus had not yet appeared in the U.S., but Chiller had been chatting with peers in other countries and had heard what happened when the microbe invaded their health-care systems. It resisted treatment by most of the few drugs that could be used against it. It thrived on cold hard surfaces and laughed at cleaning chemicals; some hospitals where it landed had to rip out equipment and walls to defeat it. It caused fast-spreading outbreaks and killed up to two thirds of the people who contracted it.

Shortly after that warning, *C. auris* did enter the U.S. Before the end of 2016, 14 people contracted it, and four died. Since then, the CDC had been tracking its movement, classifying it as one of a small number of danger-

ous diseases that doctors and health departments had to tell the agency about. By the end of 2020 there had been more than 1,500 cases in the U.S., in 23 states. And then COVID arrived, killing people, overwhelming hospitals, and redirecting all public health efforts toward the new virus and away from other rogue organisms.

But from the start of the pandemic, Chiller had felt uneasy about its possible intersection with fungal infections. The first COVID case reports, published by Chinese scientists in international journals, described patients as catastrophically ill and consigned to intensive care: pharmaceutically paralyzed, plugged into ventilators, threaded with I.V. lines, loaded with drugs to suppress infection and inflammation. Those frantic interventions might save them from the virus—but immune-damping drugs would disable their innate defenses, and broad-spectrum antibiotics would kill off beneficial bacteria that keep invading microbes in check. Patients would be left extraordinarily vulnerable to any other pathogen that might be lurking nearby.

Chiller and his colleagues began quietly reaching out to colleagues in the U.S. and Europe, asking for any warning signs that COVID was allowing deadly fungi a foothold. Accounts of infections trickled back from India, Italy, Colombia, Germany, Austria, Belgium, Ireland, the Netherlands and France. Now the same deadly fungi were surfacing in American patients as well: the first signs of a second epidemic, layered on top of the viral pandemic. And it wasn't just *C. auris*. Another deadly fungus called *Aspergillus* was starting to take a toll as well.

"This is going to be widespread everywhere," Chiller says. "We don't think we're going to be able to contain this."

WE ARE LIKELY to think of fungi, if we think of them at all, as minor nuisances: mold on cheese, mildew on shoes shoved to the back of the closet, mushrooms springing up in the garden after hard rains. We notice them, and then we scrape them off or dust them away, never per-

IN SEPTEMBER 2018 Torrence Irvin of Patterson, Calif., felt like he had picked up a cold. Seven months later he had lost 75 percent of his lung capacity. Irvin had Valley fever, a fungal infection, and his life was saved by an experimental drug.

PRECEDING PAGES: JUAN GAERTNER/Science Source



ceiving that we are engaging with the fragile fringes of a web that knits the planet together. Fungi constitute their own biological kingdom of about six million diverse species, ranging from common companions such as baking yeast to wild exotics. They differ from the other kingdoms in complex ways. Unlike animals, they have cell walls, not membranes; unlike plants, they cannot make their own food; unlike bacteria, they hold their DNA within a nucleus and pack cells with organelles—features that make them, at the cellular level, weirdly similar to us. Fungi break rocks, nourish plants, seed clouds, cloak our skin and pack our guts, a mostly hidden and unrecorded world living alongside us and within us.

That mutual coexistence is now tipping out of balance. Fungi are surging beyond the climate zones they long lived in, adapting to environments that would once have been inimical, learning new behaviors that let them leap between species in novel ways. While executing those maneuvers, they are becoming more successful pathogens, threatening human health in ways—and numbers—they could not achieve before.

Surveillance that identifies serious fungal infections is patchy, and so any number is probably an undercount. But one widely shared estimate proposes that there are possibly 300 million people infected with fungal diseases worldwide and 1.6 million deaths every year—more than malaria, as many as tuberculosis. Just in the U.S., the CDC estimates that more than 75,000 people are hospitalized annually for a fungal infection, and another 8.9 million people seek an outpatient visit, costing about \$7.2 billion a year.

For physicians and epidemiologists, this is surprising and unnerving. Long-standing medical doctrine holds that we are protected from fungi not just by layered immune defenses but because we are mammals, with core temperatures higher than fungi prefer. The cooler outer surfaces of our bodies are at risk of minor assaults—think of athlete's foot, yeast infections, ringworm—but in people with healthy immune systems, invasive infections have been rare.

That may have left us overconfident. “We have an enormous blind spot,” says Arturo Casadevall, a physician and molecular microbiologist at the Johns Hopkins Bloomberg School of Public Health. “Walk into the street and ask people what are they afraid of, and they’ll tell you they’re afraid of bacteria, they’re afraid of viruses, but they don’t fear dying of fungi.”

Ironically, it is our successes that made us vulnerable. Fungi exploit damaged immune systems, but before the mid-20th century people with impaired immunity didn’t live very long. Since then, medicine has gotten very good at keeping such people alive, even though their immune systems are compromised by illness or cancer treatment or age. It has also developed an array of therapies that deliberately suppress immunity, to keep transplant recipients healthy and treat autoimmune disorders such as lupus and rheumatoid arthritis. So vast numbers of people are living now who are especially vulnerable to fungi. (It was a fungal infection, *Pneumocystis carinii*

pneumonia, that alerted doctors to the first known cases of HIV 40 years ago this June.)

Not all of our vulnerability is the fault of medicine preserving life so successfully. Other human actions have opened more doors between the fungal world and our own. We clear land for crops and settlement and perturb what were stable balances between fungi and their hosts. We carry goods and animals across the world, and fungi hitchhike on them. We drench crops in fungicides and enhance the resistance of organisms residing nearby. We take actions that warm the climate, and fungi adapt, narrowing the gap between their preferred temperature and ours that protected us for so long.

But fungi did not rampage onto our turf from some foreign place. They were always with us, woven through our lives and our environments and even our bodies: every day, every person on the planet inhales at least 1,000 fungal spores. It is not possible to close ourselves off from the fungal kingdom. But scientists are urgently trying to understand the myriad ways in which we dismantled our defenses against the microbes, to figure out better approaches to rebuild them.

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IT IS PERPLEXING that we humans have felt so safe from fungi when we have known for centuries that our crops can be devastated from their attacks. In the 1840s a funguslike organism, *Phytophthora infestans*, destroyed the Irish potato crop; more than one million people, one eighth of the population, starved to death. (The microbe, formerly considered a fungus, is now classified as a highly similar organism, a water mold.) In the 1870s coffee leaf rust, *Hemileia vastatrix*, wiped out coffee plants in all of South Asia, completely reordering the colonial agriculture of India and Sri Lanka and transferring coffee production to Central and South America. Fungi are the reason that billions of American chestnut trees vanished from Appalachian forests in the U.S. in the 1920s and that millions of dying Dutch elms were cut out of American cities in the 1940s. They destroy one fifth of the world's food crops in the field every year.

Yet for years medicine looked at the devastation fungi wreak on the plant kingdom and never considered that humans or other animals might be equally at risk. “Plant pathologists and farmers take fungi very seriously and always have, and agribusiness has,” says Matthew C. Fisher, a professor of epidemiology at Imperial College London, whose work focuses on identifying emerging fungal threats. “But they’re very neglected from the point of view of wildlife disease and also human disease.”

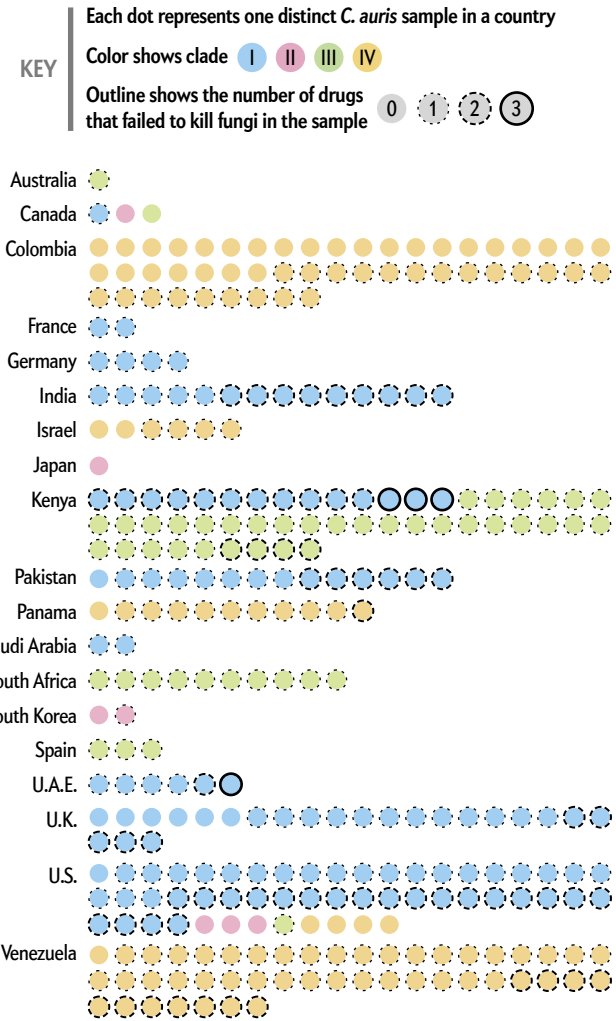
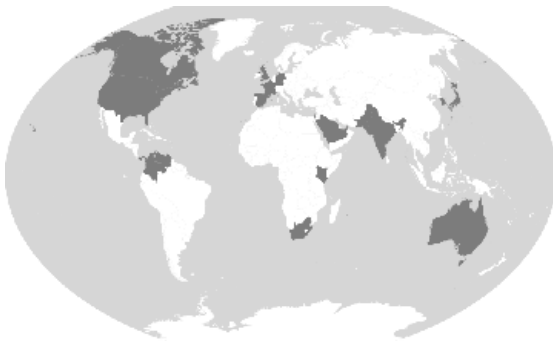
So when the feral cats of Rio de Janeiro began to fall ill, no one at first thought to ask why. Street cats have hard lives anyway, scrounging, fighting and birthing endless litters of kittens. But in the summer of 1998, dozens and then hundreds of neighborhood cats began showing horrific injuries: weeping sores on their paws and ears, clouded swollen eyes, what looked like tumors blooming out of their faces. The cats of Rio live intermingled with humans: Children play with them, and especially in poor neighborhoods women encourage them to stay near

A Drug-Resistant Killer on the Loose

The fungus *Candida auris*, a type of yeast, first appeared in the late 1990s and has spread rapidly across the globe. It is deadly to people, killing as many as two thirds of those it infects, with spores that travel through the bloodstream and bloom in major organs. A 2020 analysis found *C. auris* in 19 countries on six different continents. The fungus can be divided into four distinct genetic groups, or clades. Each clade, when tested, showed the ability to fight off at least one drug from the three major classes* of antifungals: the azoles, the polyenes and the echinocandins. Many samples were resistant to two drugs, and a few samples of clade I were impervious to three.

*There are two other classes that are not used for this type of infection.

Countries from which *C. auris* samples were tested



SOURCE: "TRACING THE EVOLUTIONARY HISTORY AND GLOBAL EXPANSION OF CANDIDA AURIS USING POPULATION GENOMIC ANALYSES," BY NANCY A. CHOW ET AL., IN AMERICAN SOCIETY FOR MICROBIOLOGY, VOL. 11, APRIL 28, 2020

houses and deal with rats and mice. Before long some of the kids and mothers started to get sick as well. Round, crusty-edge wounds opened on their hands, and hard red lumps trailed up their arms as though following a track.

In 2001 researchers at the Oswaldo Cruz Foundation, a hospital and research institute located in Rio, realized they had treated 178 people in three years, mostly mothers and grandmothers, for similar lumps and oozing lesions. Almost all of them had everyday contact with cats. Analyzing the infections and ones in cats treated at a nearby vet clinic, they found a fungus called *Sporothrix*.

The various species of the genus *Sporothrix* live in soil and on plants. Introduced into the body by a cut or scratch, this fungus transforms into a budding form resembling a yeast. In the past, the yeast form had not been communicable, but in this epidemic, it was. That was how the cats were infecting one another and their caretakers: Yeasts in their wounds and saliva flew from cat to cat when they fought or jostled or sneezed. Cats

passed it to humans via claws and teeth and caresses. The infections spread from skin up into lymph nodes and the bloodstream and to eyes and internal organs. In case reports amassed by doctors in Brazil, there were accounts of fungal cysts growing in people's brains.

The fungus with this skill was decreed a new species, *Sporothrix brasiliensis*. By 2004, 759 people had been treated for the disease at the Cruz Foundation; by 2011, the count was up to 4,100 people. By last year, more than 12,000 people in Brazil had been diagnosed with the disease across a swath of more than 2,500 miles. It has spread to Paraguay, Argentina, Bolivia, Colombia and Panama.

"This epidemic will not take a break," says Flávio Queiroz-Telles, a physician and associate professor at the Federal University of Paraná in Curitiba, who saw his first case in 2011. "It is expanding."

It was a mystery how: Feral cats wander, but they do not migrate thousands of miles. At the CDC, Chiller and his colleagues suspected a possible answer. In Brazil and Argentina, sporotrichosis has been found in rats as well

EVERY
PERSON
IN THE
WORLD
INHALES
1,000
FUNGAL
SPORES
EVERY DAY

as cats. Infected rodents could hop rides on goods that move into shipping containers. Millions of those containers land on ships docking at American ports every day. The fungus could be coming to the U.S. A sick rat that escaped a container could seed the infection in the city surrounding a port.

“In dense population centers, where a lot of feral cats are, you could see an increase in extremely ill cats that are roaming the streets,” says John Rossow, a veterinarian at the CDC, who may have been the first to notice the possible threat of *Sporothrix* to the U.S. “And being that we Americans can’t avoid helping stray animals, I imagine we’re going to see a lot of transmission to people.”

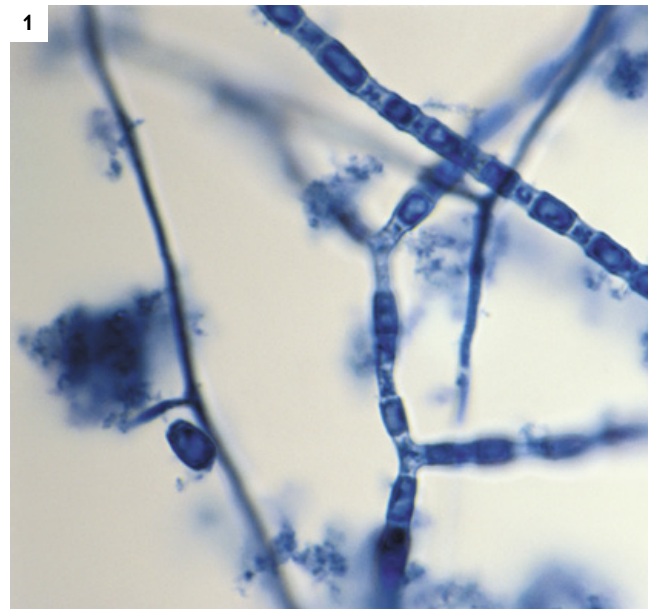
To a mycologist such as Chiller, this kind of spread is a warning: The fungal kingdom is on the move, pressing against the boundaries, seeking any possible advantage in its search for new hosts. And that we, perhaps, are helping them. “Fungi are alive; they adapt,” he says. Among their several million species, “only around 300 that we know of cause human disease—so far. That’s a lot of potential for newness and differentness, in things that have been around for a billion years.”

TORRENCE IRVIN was 44 years old when his fungal troubles started. A big healthy man who had been an athlete in high school and college, he lives in Patterson, Calif., a quiet town in the Central Valley tucked up against U.S. Route 5. A little more than two years earlier Irvin had bought a house in a new subdivision and moved in with his wife, Rhonda, and their two daughters. He was a warehouse manager for the retailer Crate & Barrel and the announcer for local youth football games.

In September 2018 Irvin started to feel like he had picked up a cold he couldn’t shake. He dosed himself with Nyquil, but as the weeks went on, he felt weak and short of breath. On a day in October, he collapsed, falling to his knees in his bedroom. His daughter found him. His wife insisted they go to the emergency room.

Doctors thought he had pneumonia. They sent him home with antibiotics and instructions to use over-the-counter drugs. He got weaker and couldn’t keep food down. He went to other doctors, while steadily getting worse, enduring shortness of breath, night sweats, and weight loss similar to a cancer victim’s. From 280 pounds, he shrank to 150. Eventually one test turned up an answer: a fungal infection called coccidioidomycosis, usually known as Valley fever. “Until I got it, I had never heard of it,” he says.

But others had. Irvin was referred to the University of California, Davis, 100 miles from his house, which had established a Center for Valley Fever. The ailment occurs mostly in California and Arizona, the southern tip of Nevada, New Mexico and far west Texas. The microbes behind it, *Coccidioides immitis* and *Coccidioides posadasii*, infect about 150,000 people in that area every year—and outside of the region the infection is barely known. “It’s not a national pathogen—you don’t get it in densely populated New York or Boston or D.C.,” says George R. Thompson, co-director of the Davis center and



the physician who began to supervise Irvin’s care. “So even physicians view it as some exotic disease. But in areas where it’s endemic, it’s very common.”

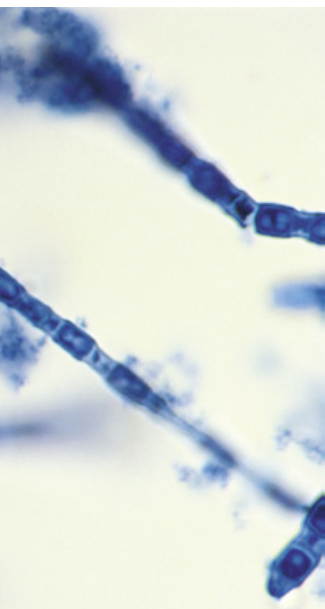
Similar to *Sporothrix*, *Coccidioides* has two forms, starting with a thready, fragile one that exists in soil and breaks apart when soil is disturbed. Its lightweight components can blow on the wind for hundreds of miles. Somewhere in his life in the Central Valley, Irvin had inhaled a dose. The fungus had transformed in his body into spheres packed with spores that migrated via his blood, infiltrating his skull and spine. To protect him, his body produced scar tissue that stiffened and blocked off his lungs. By the time he came under Thompson’s care, seven months after he first collapsed, he was breathing with just 25 percent of his lung capacity. As life-threatening as that was, Irvin was nonetheless lucky: in about one case out of 100, the fungus grows life-threatening masses in organs and the membranes around the brain.

Irvin had been through all the approved treatments. There are only five classes of antifungal drugs, a small number compared with the more than 20 classes of antibiotics to fight bacteria. Antifungal medications are so few in part because they are difficult to design: because fungi and humans are similar at the cellular level, it is challenging to create a drug that can kill them without killing us, too.

It is so challenging that a new class of antifungals reaches the market only every 20 years or so: the polyene class, including amphotericin B, in the 1950s; the azoles in the 1980s; and the echinocandin drugs, the newest remedy, beginning in 2001. (There is also terbinafine, used mostly for external infections, and flucytosine, used mostly in combination with other drugs.)

For Irvin, nothing worked well enough. “I was a skeleton,” he recalls. “My dad would come visit and sit there with tears in his eyes. My kids didn’t want to see me.”

MICHAEL ABBEY Science Source



DEADLY DUO of fungi is infecting more people. *Coccidioides immitis* causes Valley fever, and its range is spreading beyond the Southwest, where it was first identified (1). *Aspergillus fumigatus* appears in many environments and can be lethal to people suffering from the flu or COVID (2).

In a last-ditch effort, the Davis team got Irvin a new drug called olorifim. It is made in the U.K. and is not yet on the market, but a clinical trial was open to patients for whom every other drug had failed. Irvin qualified. Almost as soon as he received it, he began to turn the corner. His cheeks filled out. He levered himself to his feet with a walker. In several weeks, he went home.

Valley fever is eight times more common now than it was 20 years ago. That period coincides with more migration to the Southwest and West Coast—more house construction, more stirring up of soil—and also with increases in hot, dry weather linked to climate change. “*Coccidioides* is really happy in wet soil; it doesn’t form spores, and thus it isn’t particularly infectious,” Thompson says. “During periods of drought, that’s when the spores form. And we’ve had an awful lot of drought in the past decade.”

Because Valley fever has always been a desert malady, scientists assumed the fungal threat would stay in those areas. But that is changing. In 2010 three people came down with Valley fever in eastern Washington State, 900 miles to the north: a 12-year-old who had been playing in a canyon and breathed the spores in, a 15-year-old who fell off an ATV and contracted Valley fever through his wounds, and a 58-year-old construction worker whose infection went to his brain. Research published two years ago shows such cases might become routine. Morgan Gorris, an earth systems scientist at Los Alamos National Laboratory, used climate-warming scenarios to project how much of the U.S. might become friendly territory for *Coccidioides* by the end of this century. In the scenario with the highest temperature rise, the area with conditions conducive to Valley fever—a mean annual temperature of 10.7 degrees Celsius (51 degrees Fahrenheit) and mean annual rainfall of less than 600 millimeters (23.6 inches)—reaches to the Canadian border and covers most of the western U.S.

Irvin has spent almost two years recovering; he still takes six pills of olorifim a day and expects to do that indefinitely. He gained back weight and strength, but his lungs remain damaged, and he has had to go on disability. “I am learning to live with this,” he says. “I will be dealing with it for the rest of my life.”

SPOROTHRIX found a new way to transmit itself. Valley fever expanded into a new range. *C. auris*, the fungus that took advantage of COVID, performed a similar trick, exploiting niches opened by the chaos of the pandemic.

That fungus was already a bad actor. It did not behave the way that other pathogenic yeasts do, living quiescently in someone’s gut and surging out into their blood or onto mucous membranes when their immune system shifted out of balance. At some point in the first decade of the century, *C. auris* gained the ability to directly pass from person to person. It learned to live on metal, plastic, and the rough surfaces of fabric and paper. When the first onslaught of COVID created a shortage of disposable masks and gowns, it forced health-care workers to reuse gear they usually discard between patients, to keep from carrying infections. And *C. auris* was ready.

In New Delhi, physician and microbiologist Anuradha Chowdhary read the early case reports and was unnerved that COVID seemed to be an inflammatory disease as much as a respiratory one. The routine medical response to inflammation would be to damp down the patient’s immune response, using steroids. That would set patients up to be invaded by fungi, she realized. *C. auris*, lethal and persistent, had already been identified in hospitals in 40 countries on every continent except Antarctica. If health-care workers unknowingly carried the organism through their hospitals on reused clothing, there would be a conflagration.

“I thought, ‘Oh, God, I.C.U.s are going to be overloaded

with patients, and infection-control policies are going to be compromised,” she said recently. “In any I.C.U. where *C. auris* is already present, it is going to play havoc.”

Chowdhary published a warning to other physicians in a medical journal early in the pandemic. Within a few months she wrote an update: a 65-bed I.C.U. in New Delhi had been invaded by *C. auris*, and two thirds of the patients who contracted the yeast after they were admitted with COVID died. In the U.S., the bulletin that Chiller received flagged several hundred cases in hospitals and long-term care facilities in Los Angeles and nearby Orange County, and a single hospital in Florida disclosed that it harbored 35. Where there were a few, the CDC assumed that there were more—but that routine testing, their keyhole view into the organism’s stealthy spread, had been abandoned under the overwork of caring for pandemic patients.

As bad as that was, physicians familiar with fungi were watching for a bigger threat: the amplification of another fungus that COVID might give an advantage to.

In nature, *Aspergillus fumigatus* serves as a clean-up crew. It encourages the decay of vegetation, keeping the world from being submerged in dead plants and autumn leaves. Yet in medicine, *Aspergillus* is known as the cause of an opportunistic infection spawned when a compromised human immune system cannot sweep away its spores. In people who are already ill, the mortality rate of invasive aspergillosis hovers near 100 percent.

During the 2009 pandemic of H1N1 avian flu, *Aspergillus* began finding new victims, healthy people whose only underlying illness was influenza. In hospitals in the Netherlands, a string of flu patients arrived unable to breathe and going into shock. In days, they died. By 2018 what physicians were calling invasive pulmonary aspergillosis was occurring in one out of three patients critically ill with flu and killing up to two thirds of them.

Then the coronavirus arrived. It scoured the interior lung surface the way flu does. Warning networks that link infectious disease doctors and mycologists around the globe lit up with accounts of aspergillosis taking down patients afflicted with COVID: in China, France, Belgium, Germany, the Netherlands, Austria, Ireland, Italy and Iran. As challenging a complication as *C. auris* was, *Aspergillus* was worse. *C. auris* lurks in hospitals. The place where patients were exposed to *Aspergillus* was, well, everywhere. There was no way to eliminate the spores from the environment or keep people from breathing them in.

In Baltimore, physician Kieren Marr was acutely aware of the danger. Marr is a professor of medicine and oncology at Johns Hopkins Medical Center and directs its unit on transplant and oncology infectious diseases. The infections that take hold in people who have received a new organ or gotten a bone marrow transplant are familiar territory for her. When COVID arrived, she was concerned that *Aspergillus* would surge—and that U.S. hospitals, not alert to the threat, would miss it. Johns Hopkins began testing COVID patients in its I.C.U. with the kind of molecular diagnostic tests used in Europe,

trying to catch up to the infection in time to try to treat it. Across the five hospitals the Johns Hopkins system operates, it found that one out of 10 people with severe COVID was developing aspergillosis.

Several patients died, including one whose aspergillosis went to the brain. Marr feared there were many others like that patient, across the country, whose illness was not being detected in time. “This is bad,” Marr said this spring. “*Aspergillus* is more important in COVID right now than *C. auris*. Without a doubt.”

THE CHALLENGE of countering pathogenic fungi is not only that they are virulent and sneaky, as bad as those traits may be. It is that fungi have gotten very good at protecting themselves against drugs we use to try to kill them.

The story is similar to that of antibiotic resistance. Drugmakers play a game of leapfrog, trying to get in front of the evolutionary maneuvers that bacteria use to protect themselves from drugs. For fungi, the tale is the same but worse. Fungal pathogens gain resistance against antifungal agents—but there are fewer drugs to start with, because the threat was recognized relatively recently.

“In the early 2000s, when I moved from academia to industry, the antifungal pipeline was zero,” says John H. Rex, a physician and longtime advocate for antibiotic development. Rex is chief medical officer of F2G, which makes the not yet approved drug that Torrence Irvin took. “There were no antifungals anywhere in the world in clinical or even preclinical development.”

That is no longer the case, but research is slow; as with antibiotics, the financial rewards of bringing a new drug to market are uncertain. But developing new drugs is critical because patients may need to take them for months, sometimes for years, and many of the existing antifungals are toxic to us. (Amphotericin B gets called “shake and bake” for its grueling side effects.) “As a physician, you’re making a choice to deal with a fungal infection at the cost of the kidney,” says Ciara Kennedy, president and CEO of Amplyx Pharmaceuticals, which has a novel antifungal under development. “Or if I don’t deal with the fungal infection, knowing the patient’s going to die.”

Developing new drugs also is critical because the existing ones are losing their effectiveness. Irvin ended up in the olorofim trial because his Valley fever did not respond to any available drugs. *C. auris* already shows resistance to drugs in all three major antifungal classes. *Aspergillus* has been amassing resistance to the antifungal group most useful for treating it, known as the azoles, because it is exposed to them so persistently. Azoles are used all across the world—not only in agriculture to control crop diseases but in paints and plastics and building materials. In the game of leapfrog, fungi are already in front.

The best counter to the ravages of fungi is not treatment but prevention: not drugs but vaccines. Right now no vaccine exists for any fungal disease. But the difficulty of treating patients long term with toxic drugs, combined with staggering case numbers, makes finding one urgent. And for the first time, one might be in sight if not in reach.

ESTIMATED
FUNGAL
SPECIES:
5
MILLION
NUMBER
KNOWN
TO CAUSE
HUMAN
DISEASE:
300

The reason that rates of Valley fever are not worse than they are, when 10 percent of the U.S. population lives in the endemic area, is that infection confers lifelong immunity. That suggests a vaccine might be possible—and since the 1940s researchers have been trying. A prototype that used a killed version of the form *Coccidioides* takes inside the body—fungal spheres packed with spores—worked brilliantly in mice. But it failed dismally in humans in a clinical trial in the 1980s.

“We did it on a shoestring, and everyone wanted it to work,” says John Galgiani, now a professor and director of the Valley Fever Center for Excellence at the University of Arizona College of Medicine, who was part of that research 40 years ago. “Even with [bad] reactions and the study lasting three years, we kept 95 percent of the people who enrolled.”

Enter dogs. They have their noses in the dirt all the time, and that puts them at more at risk of Valley fever than humans are. In several Arizona counties, close to 10 percent of dogs come down with the disease every year, and they are more likely to develop severe lung-blocking forms than human are. They suffer terribly, and it is lengthy and expensive to treat them. But dogs’ vulnerability—plus the lower standards that federal agencies require to approve animal drugs compared with human ones—makes them a model system for testing a possible vaccine. And the passion of owners for their animals and their willingness to empty their wallets when they can may turn possibility into reality for the first time.

Galgiani and his Arizona group are now working on a new vaccine formula, thanks to financial donations from hundreds of dog owners, plus a boost from a National Institutes of Health grant and commercial assistance from a California company, Anivive Lifesciences. Testing is not complete, but it could reach the market for use in dogs as early as next year. “I think this is proof of concept for a fungal vaccine—having it in use in dogs, seeing it is safe,” says Lisa Shubitz, a veterinarian and research scientist at the Arizona center. “I really believe this is the path to a human vaccine.”

This injection does not depend on a killed Valley fever fungus. Instead it uses a live version of the fungus from which a gene that is key to its reproductive cycle, *CPSI*, has been deleted. The loss means the fungi are unable to spread. The gene was discovered by a team of plant pathologists and later was identified in *Coccidioides* by Marc Orbach of the University of Arizona, who studies host-pathogen interactions. After creating a mutant *Coccidioides* with the gene removed, he and Galgiani experimentally infected lab mice bred to be exquisitely sensitive to the fungus. The microbe provoked a strong immune reaction, activating type 1 T helper cells, which establish durable immunity. The mice survived for six months and did not develop any Valley fever symptoms, even though the team tried to infect them with unaltered *Coccidioides*. When the researchers autopsied the mice at the end of that half-year period, scientists found almost no fungus growing in their lungs. That long-last-

ing protection against infection makes the gene-deleted fungus the most promising basis for a vaccine since Galgiani’s work in the 1980s. But turning a vaccine developed for dogs into one that could be used in humans will not be quick.

The canine formula comes under the purview of the U.S. Department of Agriculture, but approval of a human version would be overseen by the U.S. Food and Drug Administration. It would require clinical trials that would probably stretch over years and involve thousands of people rather than the small number of animals used to validate the formula in dogs. Unlike the 1980s prototype, the new vaccine involves a live organism. Because there has never been a fungal vaccine approved, there is no preestablished evaluation pathway for the developers or regulatory agencies to follow. “We would be flying the plane and building it at the same time,” Galgiani says.

He estimates achieving a Valley fever vaccine for people could take five to seven years and about \$150 million, an investment made against an uncertain promise of earnings. But a successful compound could have broad usefulness, protecting permanent residents of the Southwest as well as the military personnel at 120 bases and other installations in the endemic area, plus hundreds of thousands of “snowbird” migrants who visit every winter. (Three years ago the CDC identified cases of Valley fever in 14 states outside the endemic zone. Most were in wintertime inhabitants of the Southwest who were diagnosed after they went back home.) By one estimate, a vaccine could save potentially \$1.5 billion in health-care costs every year.

“I couldn’t see the possibility that we’d have a vaccine 10 years ago,” Galgiani says. “But I think it is possible now.”

IF ONE FUNGAL VACCINE is achieved, it would carve the path for another. If immunizations were successful—scientifically, as targets of regulation and as vaccines people would be willing to accept—we would no longer need to be on constant guard against the fungal kingdom. We could live alongside and within it, safely and confidently, without fear of the ravages it can wreak.

But that is years away, and fungi are moving right now: changing their habits, altering their patterns, taking advantage of emergencies such as COVID to find fresh victims. At the CDC, Chiller is apprehensive.

“The past five years really felt like we were waking up to a whole new phenomenon, a fungal world that we just weren’t used to,” Chiller says. “How do we stay on top of that? How do we question ourselves to look for what might come next? We study these emergencies not as an academic exercise but because they show us what might be coming. We need to be prepared for more surprises.” ■

FROM OUR ARCHIVES

Fungi on the March. Jennifer Frazer; December 2013.

[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)



PLANETARY SCIENCE

THE BROKEN SHIELD

Scientists just lost one of their best tools
for defending Earth against
potentially dangerous asteroids.

What comes next?

By Sarah Scoles

BITS OF GREEN peek through cracks
in the Arecibo telescope's dish after cables
snapped and it collapsed in late 2020.

Sarah Scoles is a Denver-based science writer, 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).



IN THE FIRST FEW SECONDS OF VIDEO TAKEN AT THE ARECIBO RADIO TELESCOPE ON December 1, 2020, everything looks normal. Sure, support cables had broken the previous August and November, damaging the 300-meter-wide dish. And *sure*, the National Science Foundation was already planning to decommission Arecibo, an instrument that began scanning the sky in 1963. So things weren't great for the telescope. But it was at least still there.

That changed just before 8 A.M. when, as if on command, a bit of dust puffed out from a support pillar. That was, it turns out, a cable beginning to snap off. Left with extra load, other cables began to break, too. Soon the massive equipment platform, once suspended over the bowl-shaped observatory, began to tip. After an agonizing swing downward, the platform crashed. More cables snapped, and debris flew around like in a demolition. At the end of the footage, giant holes were visible in the iconic telescope, and dust rose all around. Arecibo, at least as scientists knew it, was gone.

When Edgard Rivera-Valentín, a staff scientist at the Lunar and Planetary Institute and formerly part of the planetary radar group at Arecibo, clicked on the video, they could stomach only a few seconds. It took them days to get through the full two minutes. “When everything went down, it was—I use the word ‘tragedy,’” says Rivera-Valentín, a native of Puerto Rico.

Arecibo had a long and storied legacy of scientific discovery, studying space weather, searching for extraterrestrials, timing pulsars, mapping neutral hydrogen gas. But it also had an unconventional claim to fame: It boasted the world's most powerful, sensitive and active planetary radar system. That radar could peer through Venus's thick atmosphere and map the dusty Martian surface, but it also helped protect Earth from asteroids. The data showed scientists those rocks in detail, revealed whether they might present a threat, and helped humans figure out what they could reasonably do if an asteroid was heading our way. “One of the neat things about doing radar is that you're actively defending the entire Earth,” Rivera-Valentín says. “So if anyone asks you, ‘Why should I care?’, it's like, ‘I'm go-

ing to make sure that asteroid doesn't come for you.’”

Arecibo's radar efforts fell under the umbrella of “planetary defense”: the attempt to identify and prevent potential collisions between asteroids (and comets) and this planet, which, ideally, we would like to keep intact.

On any given day the likelihood is low that a space rock will devastatingly smash into Earth. But the consequences of such a catastrophe would be severe. And our solar system's history—planets pocked with craters, crashes on other planets in recent memory, huge objects hurtling through Earth's atmosphere and captured on dashcams—demonstrates the statistical truth that events unlikely to happen on any given day do happen, given enough days. That's why NASA has an entire office dedicated to the problem; why a slew of astronomical facilities gather preventive data; and why an upcoming space mission will demonstrate what earthlings can do if a space rock does come knocking.

But is it enough? With Arecibo and its radar out of commission, our planetary defense arsenal comes up short. The U.S. and other nations are assessing the risk, brainstorming new ways to stay ahead of the threat and formulating plans for what might come next.

COUNTING SPACE ROCKS

PLANETARY DEFENSE has been plagued by a “giggle factor.” After all, apocalypse by asteroid seems the stuff of feature films, not serious science. But officials started to pay more attention soon after a comet called Shoemaker-Levy headed straight for Jupiter in 1994. Linda Billings, a consultant for NASA's planetary defense communications efforts, remembers when the two collided. On July 21, 1994—a few days into a series of impacts—she went to an

PRECEDING PAGES: CAVANI IMAGES/Alamy Stock Photo



open house at the Naval Observatory in Washington, D.C., where sky watchers could spy on Jupiter. On the lawn outside, amateur astronomers trained their own instruments on the scarred planet. Jupiter's gravity had shredded the comet into pieces, which streamed into the planet's swirling atmosphere, reaching 40,000 degrees Celsius and sending 3,000-kilometer-high plumes of material shooting into space. "We had solid evidence that impacts occur," Billings says, understatedly.

Soon after, U.S. Air Force officials published two reports, *SpaceCast 2020* and *Air Force 2025*, on what the military could or should do to mitigate the threat of space rocks in the coming decades. Space impacts were a national security problem. The first report, meant to figure out how the U.S. could maintain the "high ground" in space, coined the term "planetary defense." The second had much the same goal, and both described asteroid detection and mitigation, the word for efforts to dispense with a threat if one arises—by, for instance, deflecting an asteroid by slamming into it with a spacecraft or exploding a nuclear weapon nearby.

Back then, scientists now well known for their planetary protection work were part of the air force—people such as Lindley Johnson, now program executive of NASA's Planetary Defense Coordination Office (and an author of the relevant part of *SpaceCast*), and Pete Worden, former director of NASA's Ames Research Center. They and their colleagues warned about the risk of civilization turning into a crater. But especially after 9/11, the issue

did not receive as much attention as many would have liked. Johnson retired from active duty in 2003. "NASA said, 'Come on over. We've got a job for you,'" he says. One of his duties was to run NASA's Near-Earth Object Observations program. Today, in large part a result of Johnson's efforts, that has mushroomed into an entire Planetary Defense Coordination Office, where he is the boss. "An unwarned impact would be the biggest natural disaster we've ever seen, quite frankly," Johnson says. His office hopes to make any hypothetical impact an avoidable one.

To that end, NASA's office runs asteroid data-gathering programs, relying in part on wide-field optical and infrared telescopes that can see a broad expanse of the sky. Observatories run by the University of Arizona and the University of Hawaii have worked with Johnson's office to adapt their existing telescopes into sentries. The group also repurposed the space-based Wide Area Infrared Survey Explorer (WISE) into NEOWISE (Near-Earth Object WISE) in the years after it was initially decommissioned in 2011. NEOWISE recently completed its 14th all-sky survey and is working on its 15th.

Meanwhile M.I.T. Lincoln Laboratory's Lincoln Near-Earth Asteroid Research (LINEAR) software is currently installed on an air force asset called the Space Surveillance Telescope (SST) in Australia. The software makes this military observatory the world's most productive asteroid-hunting instrument, by some metrics. It has discovered 142 previously unknown near-Earth objects, four potentially hazardous objects and eight new comets.

ON THE MORNING of February 15, 2013, an asteroid the size of a house entered Earth's atmosphere and exploded over Chelyabinsk, Russia. The event was a reminder of the potential perils of rocks falling from space.

That's great but not as good as Congress would like. The official mandate these days is to discover 90 percent of the objects that are 140 meters or larger—the size at which a boom would result in “a pretty bad day anywhere,” according to Johnson. There are an estimated 25,000 such baddies. “We are getting close, and maybe by the end of the year we’ll have found 10,000 of those,” he says. That is 40 percent completion for 20 years of effort. Overall, scientists have discovered more than 25,000 near-Earth asteroids of any size, and around 19,000 of those caught on camera are bigger than 30 meters.

REPLACING ARECIBO

GLOBALLY, 30 SPACE ORGANIZATIONS—based everywhere from Latvia to Colombia, from China to Israel, and involving dedicated amateurs, national space agencies and individual observatories—participate in the International Asteroid Warning Network. The group, formed at the recommendation of the United Nations, coordinates observation and response efforts across our vulnerable planet. Since 2016 it has logged more than 300 close approaches, when asteroids were projected to come within one lunar distance—the average distance between Earth and the moon—of the globe’s center. It has also coordinated three campaigns to practice “the observing resources and characterization capabilities that may be applied to a near-Earth object on a reasonably short timescale.”

That is useful because the work is not finished when close-calling objects are discovered. Ground-based optical and infrared telescopes in places such as Hawaii, New Mexico and Arizona make follow-up observations to learn more about the objects than the fact of their existence. Planetary radar, too, typically plays a role in refining the orbits of newly discovered asteroids and projecting their paths into the future—mapping out where those objects will go in the years to come and whether they might intersect with Earth. Radar also helps to discern asteroids’ shape, composition and trajectory.

Radar observations such as Arecibo’s work like this: If you blast powerful radio waves toward the object, they bounce back, changed by the object’s spin, motion, shape and size, as well as by any moons the asteroid might have. The time they take to holler back also reveals the object’s precise distance from Earth. With all that information, you can refine its orbit and predict where it will be far into the future and whether that “where” includes Iowa. You can also learn about its properties—useful if you must knock it off course. Is it dense? Porous? Round? Peanutty? “When we record the echo that comes back, if it’s different in any way from what we transmitted, we know that was due to the properties of the target, in this case, the asteroid,” says Patrick Taylor, a senior staff scientist at the Lunar and Planetary Institute and former group lead for Arecibo’s radar program.

Getting a radar observation is like taking a picture of the asteroid from the safety of the ground. “That is kind of like a flyby of a spacecraft at a tiny fraction of the cost,” says Ellen Howell of the University of Arizona. “We get pictures of them as individual rocks, not just points of

light.” Which is significant, because as planetary scientists are fond of saying, if you’ve seen one asteroid, you’ve seen one asteroid. With the loss of Arecibo, Howell says, “that capability is now severely diminished.” This ability to take observations of the present, predict the future and then *change* the future is what could set us apart from the poor saps of the past, who just had to take whatever knocks space sent their way. “Dinosaurs didn’t have a space program,” Rivera-Valentín says. “But we do.”

Arecibo was not the only planetary radar in the U.S. There is one left—the Goldstone Solar System Radar in California—but it can detect less than half the near-Earth asteroids that Arecibo could. And even if Goldstone were the perfect instrument, stuff happens, and if it is down—as it was for around 18 months of maintenance just before Arecibo collapsed—this planet will have to fly through space without seeing as much as it previously did. “Losing Arecibo is going to make people think more about what that next-generation step will be,” Taylor says. “Whatever that is, I don’t know.”

Scientists have ideas. Some would like to build Arecibo 2.0, synthesizing a number of smaller dishes in the same island spot to work together as one larger dish, thereby restoring radar capabilities. At Green Bank Observatory in West Virginia, scientists just did their own demo with defense contractor Raytheon, beaming a radar signal to the moon and receiving the bounce-back at antennas spread throughout the U.S. in the Very Long Baseline Array, which is operated from New Mexico. They hope this will pave the way for a setup with more oomph that could do asteroid work. “The Green Bank proposal for upgrade sounds terrific to me,” Billings says. “But it’s not yet funded.”

And even if it were, Michael Nolan of the University of Arizona doubts that Green Bank could replace Arecibo’s capabilities. Transmitting from one spot and picking up in another is a data-intensive approach, and doing both from Green Bank has its own issues. “I don’t see any of the things I’ve seen so far being the workhorse system,” he says. Arecibo’s hypothetical replacement does not have funding either, for instance.

And the question of what to do is only the first hurdle. There is also the larger issue of who should do it. Some experts argue that the burden is too much for the scientific community to bear alone. Perhaps, they say, the task should fall to an organization with extensive experience in long-term planning and, more important, stable funding. In other words, the Department of Defense—specifically, its newly minted Space Force.

STOPPING ASTEROIDS

THE SPACE FORCE, a new branch of the military that largely deals with satellites and their safety and security, aims to track objects large and small, from here to the moon, as international and commercial activity—satellites, spacecraft, orbital manufacturing systems, pay-as-you-go trips—ramps up. That general effort is called space situational awareness, and it is usually carried out by optical instruments and long-range radar. While that radar is monitor-

How to Deflect an Asteroid

What if scientists discover a large space rock heading toward Earth? Humanity has several options to try to move the body off course, although none have been tested. Some, such as using a nuclear weapon on the incoming rock, bring their own risks—for instance, the possibility that debris from the explosion could still reach our planet.

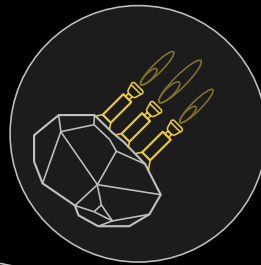
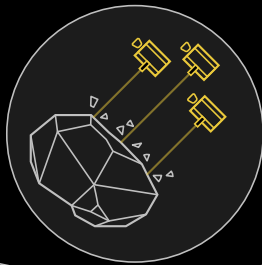
POSSIBLE DEFLECTION METHODS

Fly a heavy spacecraft near the rock to act as a “gravity tractor,” influencing the rock’s direction over decades.

Shoot lasers from small spacecraft to vaporize material, which flies off the surface and creates a push in the opposite direction.

Shine a mirror to redirect sunlight, causing the rock to shed material, which gives it a nudge.

If the asteroid is solid enough, land equipment on the surface to propel it with rockets.



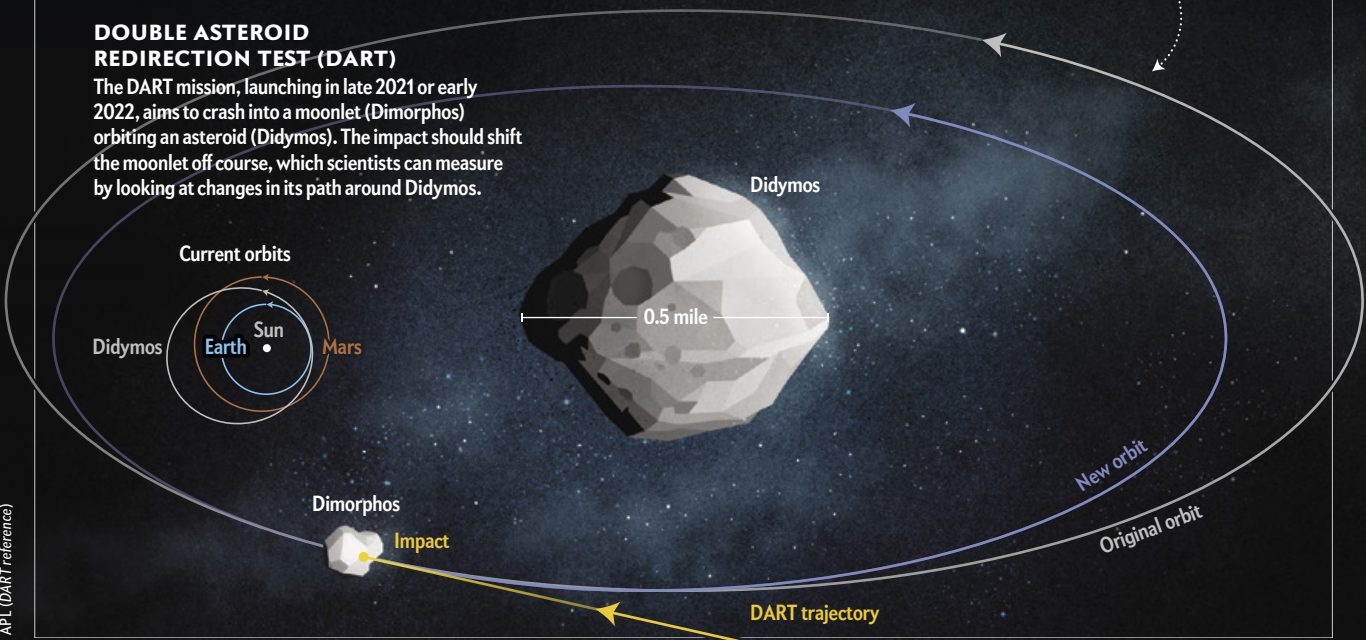
Paint it to alter its thermal properties so that sunlight will change its direction.

Detonate a nuclear weapon near an object, transferring energy and pushing it off course.

Slam an asteroid with a spacecraft before it slams into Earth. Scientists hope to test this method with DART.

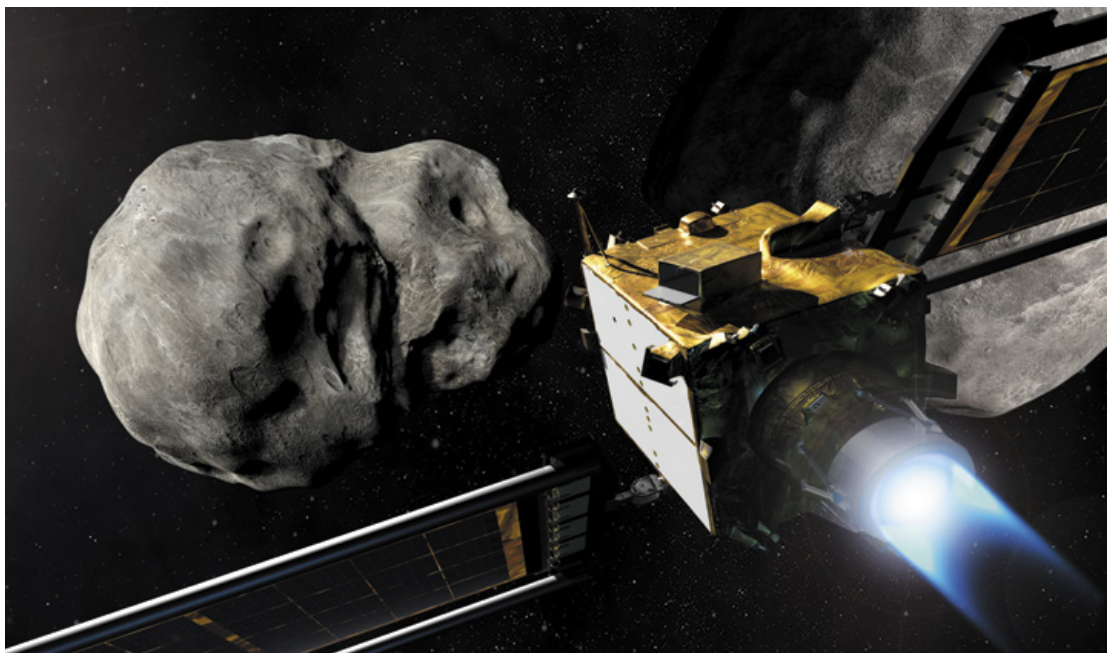
DOUBLE ASTEROID REDIRECTION TEST (DART)

The DART mission, launching in late 2021 or early 2022, aims to crash into a moonlet (Dimorphos) orbiting an asteroid (Didymos). The impact should shift the moonlet off course, which scientists can measure by looking at changes in its path around Didymos.



SOURCE: NASA, JOHNS HOPKINS APL (DART reference)

DUE TO LAUNCH
this year or next, the Double Asteroid Redirection Test (DART) will try to alter the course of a space rock by slamming into it.



ing the activity in orbit, it could also detect asteroids that happen to be zooming through space in the same direction as (but, it is hoped, much farther out than) a satellite. NASA and Space Force officials have been talking about collaborating on such a win-win system. “It is beyond just brainstorming, but we have not settled on a particular concept yet,” says Johnson, noting that the discussions are ongoing. In 2020 the two organizations signed a memorandum of understanding, agreeing to work together on certain things—including both planetary defense and space situational awareness. The Space Force referred questions about the collaboration back to NASA.

Some, though, want to expand the idea of military involvement. Peter Garretson, a senior fellow at the American Foreign Policy Council and former director of Air University’s Space Horizons Research Task Force, would like to see the military lead planetary defense efforts, particularly mitigation. “NASA is principally a science and exploration agency. In my view, this is clearly a defense mission,” Garretson says. “You’re not deflecting the asteroid for science.”

And actually *no* federal organization is specifically tasked with deflecting asteroids. But people are working on it anyway. One agency stepped in the effort is the Department of Energy—you know, the one with the nukes. At Los Alamos National Laboratory, Cathy Plesko does asteroid mitigation research. She got into planetary defense by studying impact craters on Mars using computer models. “But how do you *stop* making a crater?” she wondered. One day a senior astrophysicist at the lab said he thought the same sorts of code she used to model the craters could be used to model asteroid mitigation: They would show how an asteroid would react if something impacted it—rather than if it impacted something. This was the very stoppage she was wondering about.

She began studying the problem, but the lab’s efforts weren’t extensive—until February 2013. That month a 20-meter-wide asteroid screamed through the atmosphere and exploded nearly 30 kilometers above Chelyabinsk Oblast in Russia with the force of around 450 kilotons of TNT, injuring 1,600 people. As with Shoemaker-Levy, officials opened their eyes wider. Plesko’s team spooled up and, together with NASA, started scrambling to understand what physics problems they needed to solve to respond if something bigger and badder came along. That work begins with revealing what asteroids are made of, a surprisingly hard problem to which radar provides the best Earth-based solution. “Are they rubble piles? Are they kind of mud balls? Are they chunks of iron?” Plesko asks. “There’s a lot of variety.” That variety makes simulations difficult. If you are modeling a plane on a computer, you know exactly how dense it is and how it is shaped. “We don’t have those specifications for asteroids and comets,” she says. “That’s something we have to figure out.”

Today Plesko examines the plethora of possibilities to whisk different kinds of asteroids away from the globe. One option is called a gravity tractor. You fly as heavy a spacecraft as you can muster as close to a space rock as you can sidle. “Your spacecraft can sort of lure the asteroid or the comet off its original course over time,” she says. But it requires decades of luring, and the technology, she estimates, will not be ready for a century or so.

Some scientists have looked at using lasers attached to small spacecraft to heat up material and vaporize it, throwing it off the surface and thus—every action resulting in another equal and opposite—pushing the asteroid in the other direction. More bluntly, one could also slam an asteroid with a spacecraft before it slams into Earth. Alternatively: Shine a mirror at it, focusing solar

NASA, JOHNS HOPKINS APL

rays, until it sheds material. Move it with rockets. Paint it to change its thermal properties and thus its orbit. Plesko, being at the Department of Energy, also studies the boomier menu choice: a “nuclear standoff burst.” That means detonating a nuclear weapon close to a near-Earth object, transferring energy and throwing off some material. That deflects the rock just like the other techniques, only more, you know, emphatically. But studies on exploding bombs on or below the surface of an asteroid suggest that they might break up into smaller pieces that present their own problems. Either way, this option gets complicated quickly given the nature of nuclear bombs and the international ban on placing weapons of mass destruction in space. A country could use “preparing for asteroids” as an excuse for nuclear proliferation; furthermore, an asteroid is a global threat, but a single country would be using its own arsenal to fight it. “No one takes that lightly,” Plesko says.

Every two years the global community stages a Dungeons-and-Dragons-style role-playing game, in which agencies act out their response to a fictional planetary defense scenario. Information about the “impact scenario” gets posted online ahead of time, with more revealed each day in PowerPoint-style briefings. In 2019, ahead of their arrival at the conference, participants knew a rock between 100 and 300 meters across had a 1 percent change of hitting Earth eight years in the future. By day three they knew it was 260 meters long and 140 meters wide, dead set on a straight course to Denver.

While the group developed a mission to deflect the problem object, a broken-off piece 60 meters across nonetheless set a course for Manhattan. The role players switched to disaster-dealing mode, looking at how to evacuate, what to do about chemical factories and nuclear plants, and what the economic fallout would look like. The gamers returned to the tabletop this year (via video-conference) to investigate an asteroid that could come calling in just six months. The entire exercise “gives a reality check on how long it takes to do things,” Plesko says. It’s not like in Hollywood, she adds, which goes more like, “An asteroid is discovered; let’s launch the thing.” Still, responding in a meaningful way is something humans can accomplish, even if more slowly than on-screen.

A TEST RUN

SOON AN AUDACIOUS MISSION will test our ability to move mountains in space. Due to launch in late 2021 or early 2022, DART—the Double Asteroid Redirection Test—will aim to demonstrate that we can change an asteroid’s path like that of a wayward teen. Andrew Rivkin, one of the mission’s investigation team leads, started studying asteroids for the fundamental science—the “origins of the solar system” stuff. “No matter what you’re trying to answer, it kind of comes back to asteroids somehow,” he says. Plus, he adds, you can buy pieces of them on eBay.

Or you can build a spacecraft to shove one around, as Rivkin is now doing. DART will travel to the Didymos system, which has a large asteroid called Didymos and a small moon called Dimorphos. Then the spacecraft

will slam into the moon, changing its orbit around its bigger sibling and thus the bigger sibling’s motion around the sun. The 610-kilogram spacecraft will hit the 4.8-billion-kilogram (“small”) Dimorphos at a speed of 6.58 kilometers per second, changing (scientists think) its orbital period by about 10 minutes. Because Dimorphos itself is the size of an asteroid that could endanger cities, scientists hope to see how well they can transfer momentum from a spacecraft to a space rock. It is the medium-sized mitigation option, midway between “you nuke it, or you hide in the basement,” as Rivkin frames it. It is also preventing an impact by making an impact. The general technique would work in single-asteroid systems, too—you can slam a spacecraft into a loner—but scientists have a good reason for choosing a double system for this test: it is simple to measure how much you changed a moon’s orbit because you can just watch it pass in front of the larger asteroid in real time.

Scientists will get their first view of the system—as a single pixel—about a month before the smashup in 2022. “That one pixel is what we’re trying to guide toward,” says Elena Adams, the mission systems engineer. An hour before arrival, they will glimpse the moon and begin navigating toward it. “And then *bam*, we lose all contact, which is good,” Adams says. It means things have gone boom. (“Somebody pays you to do that, right?” Adams exults. “You get to destroy a \$250-million spacecraft!”)

The team hopes that the Goldstone radar, as well as space telescopes, will also watch the show. “We hoped Arecibo would,” Rivkin says sadly. The data gathered, then and after the fact, will be fed into future models that scientists such as Plesko use to determine how to respond to an actual asteroid threat. “Programs like DART, they’re insurance in case we do find something,” Rivkin says. People pay for fire insurance and flood insurance; they check their basements for radon. “We are hoping and expecting that the radon test won’t find any radon and the house is not going to catch fire or flood, but we are kind of doing our due diligence.”

Although Rivkin is glad people no longer think of planetary defense as a joke and instead can fathom the utility of cosmic insurance, he cautions against space rock anxiety. “If people are being kept up at night by asteroids, hopefully it’s thinking about all the cool science,” he says. It is that science, in fact—figuring out how to detect, track, project and characterize these lonesome travelers—that enables the whole of planetary defense. And planetary defense, in turn, enables humans to wrest some control from the cosmos. “This is the first time as a species we have the opportunity to prevent a natural disaster,” Plesko says. “We can’t stop a hurricane or prevent earthquakes. We can’t just go superglue the San Andreas Fault shut.” But stopping a planet killer? “If we needed to,” she says, “I really do believe we could do this.” ■

FROM OUR ARCHIVES

Stop the Killer Space Rocks, Edward T. Lu; December 2011.

scientificamerican.com/magazine/sa

CLIMATE CHANGE

THE POLAR CRUCIBLE

A warming climate brings sweeping changes
to the world's northernmost town

By Gloria Dickie

Photographs by Marzena Skubatz



LONGYEARBYEN is wedged between barren mountains and an increasingly ice-free fjord on the Norwegian archipelago of Svalbard. Rapidly rising temperatures are making the region more physically unstable yet more economically alluring.

Gloria Dickie is an environmental journalist based in British Columbia, Canada. Her work appears in *National Geographic*, *Wired*, the *New York Times*, and elsewhere.



Mark Sabbatini first noticed

the cracks in his apartment's concrete walls in 2014. It had been six years since he moved to Svalbard, a Norwegian archipelago far out in the Barents Sea, about halfway between Norway's northern tip and the North Pole. He was an itinerant American writer drawn by promises of an open, international society—and jazz music. Every winter the community of Longyearbyen, the world's northernmost town at 78 degrees North latitude, holds a jazz festival to liven up the perpetual darkness. Residents, university students, tourists and visiting scientists mingle in music halls, clinking champagne glasses to melodious tones as winds howl through the surrounding mountains. On his first visit Sabbatini had arrived just in time for the festivities. Svalbard, he says, instantly felt like home. “It was like when you look across the room and spot somebody and fall in love.”

But fissures were now appearing in the relationship. Sabbatini worried the apartment cracks were caused by a leaky roof; it *had* been raining more than usual. Then he realized the building's concrete foundation was buckling. Fractures slithered up the stairwells and defaced the building's beige exterior. The next year tenants discovered that part of a cooling system underneath the building, meant to help keep the permafrost ground frozen and stable during warm spells, was faltering. “And we were getting *a lot* of warm spells,” Sabbatini says. Suddenly, on a February afternoon in 2016, town officials ordered the occupants to evacuate, afraid the building could





1

SUKKERTOPPEN mountain, 370 meters (1,214 feet) high, looms over the town; a 2015 avalanche down its slope killed two residents (1). Fruene cafe on the central square is a local hotspot (2). The Svalbard Global Seed Vault, repaired after damage in 2017 from heavy rains and weakened permafrost, is several kilometers west of town (3).



2



3



collapse. Sabbatini and 29 others had only a few hours to pack and get out.

Some of the evacuees left Longyearbyen, but Sabbatini, now 53, stayed. Today he is one of about 2,400 residents who call the place home—the fastest-warming town in the world. Since 1971 temperatures on Svalbard have risen by roughly four degrees Celsius, five times faster than the global average. In winter it is more than seven degrees C warmer than it was 50 years ago. Last summer Svalbard recorded its hottest temperature ever—21.7 degrees C—following 111 months of above-average heat. True to Sabbatini's observations, annual precipitation on Svalbard has increased by 30 to 45 percent over the past 50 years, largely in the form of winter rain, according to the Norwegian Meteorological Institute. And the archipelago's permafrost—ground that should remain largely frozen—is now warmer here than anywhere else at this latitude. Even by Arctic standards, Svalbard is heating up fast.

The consequences are extensive. The thawing permafrost, which can heave or slump, has ruptured roads and exposed the macabre contents of old graves. Extremely windy, heavy snowstorms—once rare—have triggered deadly avalanches on the mountain slopes looming above Longyearbyen. Yet the snow season is shorter. The sea ice is retreating. Glaciers that reach down from the mountains are among the most rapidly melting on earth, according to a 2020 *Nature Communications* study. Svalbard's polar bears and reindeer are struggling to find food.

As climate change distorts the Arctic ecosystem, it is also unlocking economic potential. After explorer Willem Barents discovered the archipelago in 1596, Dutch, British and Danish sailors established Svalbard as a whaling outpost and slaugh-

DAMAGED BUILDINGS may end up abandoned (1). When permafrost thaws, concrete structures can crack; Mark Sabbatini's first apartment was one victim (2). A blizzard this past April shut down roads (3).

tered the plentiful cetaceans to meet European demand for lamp oil. When the marine mammals were depleted in the early 1900s, rough-handed entrepreneurs from Norway, Russia, and elsewhere pivoted to mining coal. Today mining is waning, but valuable fishes are migrating to the warming waters, and ice-free seas are opening access for cruise ships and for oil and gas exploration under the seafloor.

Change is happening across the High North. In Alaska, crumbling permafrost cliffs are falling into the Bering Sea, forcing coastal residents to move inland. Greenland's melting ice sheet is exposing rare-earth minerals, drawing outside investment from nations such as China. Danish container ships have begun transiting the ice-free Northern Sea Route that parallels Siberia's coast.

The Norwegian archipelago is unique among its Arctic peers, however, because of its governance and strategic location. The Svalbard Treaty signed after World War I granted Norway sovereignty over the islands. The Soviets had their settlements—Barentsburg and Pyramiden—and Norway had Longyearbyen. No Indigenous group has ever occupied the land. Norway was chosen as steward because of its proximity and its historical activity in the area—and because it was in good standing with the Allied powers. The treaty charged Norway with protecting the archipelago, but it also contained a



2



3

“nondiscrimination principle” allowing any citizen of the now 46 signatory countries, including North Korea, to live on Svalbard, no visa needed. Non-Norwegians can open businesses, mine and fish like a Norwegian. No other place in the world is as open to outsiders. Fishers are following the fish, oil and gas prospectors are testing the waters and young workers in the tourist trade are heading to Svalbard seeking adventure. The islands—with a land area similar to that of West Virginia—are also receiving attention because they are midway between Russia and the Western Hemisphere, offering a critical military vantage point. Russia’s military ships and nuclear submarines traveling to the Atlantic Ocean routinely pass nearby.

What was once an isolated, stable society cloaked in semi-permanent darkness has been thrust to the forefront of Arctic change by rapid warming and the interests that warming precipitates. Whether Norway can preserve Longyearbyen’s character and peaceable community will be a test that many Arctic communities will soon have to face.

UNCERTAIN GROUND

LONGYEARBYEN lies near the inland end of Adventfjord, a U-shaped bay off the Arctic Ocean. Barren mountains rise to the east and west, walling in the three-kilometer-long town with rock and ice. There is not a tree or bush in sight.

I first experienced this landscape on a visit in 2018. On a late January morning I stepped out of my hostel at the southern end of Longyearbyen into the “civil twilight,” a period of blue gloom at the end of the polar night before the sun begins to break the horizon again. I walked up the main street to the central plaza, watched over by a dark metal statue of a bearded

miner. The town’s heated, aboveground water and sewer pipes ran along my left side, as did the narrow Longyear River, which flows down from two glaciers to meet Adventfjord’s cobalt waters at the town’s northern end. The twilight revealed fractured and abandoned buildings sinking into the ground, including Sabbatini’s old apartment. In past winters Svalbard’s smaller fjords froze over, providing refuge for the blubbery ringed seals that lived in the harbor, but the dark blue water in Adventfjord, visible up ahead of me, had not frozen firmly since late 2014.

Cold, white light from the moon glinted off steel snow fencing strung along ridgelines above, a reminder of the rising risk of avalanches. In December 2015 an avalanche had stampeded down onto the town’s eastern neighborhood, burying 11 homes. A man and toddler died. Fourteen months later another avalanche crashed onto two apartment buildings. When scientists surveyed the mountain, they surmised that storms were bringing short, intense bouts of snow. Strong winds packed the snow into slabs vulnerable to sudden collapse. The risk of landslides and mudslides has increased, too.

When I reached the square, I ducked inside Fruene, the cafe where I was to meet Sabbatini. He spent much of his time there working on his hyperlocal newspaper *Ice People*. The cafe was filled with residents and tourists sipping cappuccinos and nibbling chocolates shaped like polar bears. “Everyone loves the dark season here,” Sabbatini told me as we sat down, his head covered in a wool toque. “There’s just so much going on.” His beloved Polarjazz festival was due to return in two days, and he eagerly recited the list of performances.

He ended up missing all of them. The day after we met, Sab-

batini slipped on the ice outside his new residence and broke his hip. He had to be flown to the mainland for treatment. A few weeks earlier the mercury had reached six degrees C—once unheard of in January. The clouds chucked down 44 millimeters of rain, not snow. When the wet ground froze, it formed a treacherous sheet of ice that had persisted since.

“When I came here [in 2008], it was typical that you would see snow every month of the year,” Sabbatini told me when I reconnected with him on the phone more than 12 months later. “It was typical that the seas here in the western part of Svalbard would freeze over every year. Neither of those is true anymore.”

His apartment evacuation, he continued, “was just a preview of what was to come.” After the avalanches, the town found that nearly 140 residences were in an avalanche danger zone, as were university dorms and tourist hostels. “Suddenly, you’re talking about housing for about 20 percent of the population wiped out,” Sabbatini said. “All due to climate. That’s just staggering.”

Scientists expect the land to become less secure. More rain and more meltwater will raise river levels, leading to more flooding and erosion, says Hege Hisdal, director of hydrology at the Norwegian Water Resources and Energy Directorate.

In 2008 it was typical to see snow every month. Seas would freeze every year. Neither of those is true any more.

Since 2009 deep permafrost temperatures have increased at rates between 0.06 and 0.15 degree C per year. When permafrost warms, its active layer—the top layer of soil that thaws during the summer and freezes in autumn—grows deeper. Around Longyearbyen the thaw is deepening by 0.5 to two centimeters annually, and the town’s structural instability deepens with it.

Across the Arctic, scientists estimate that with two degrees C of warming, 2.5 million square kilometers of permafrost could thaw and disappear. In Newtok, Alaska, more than a kilometer of eroding permafrost cliffs along the town’s edge have crumbled into the sea, forcing the Indigenous Yup’ik residents to move inland. There environmental challenges are compounded by political ambivalence; as early as 2003, the U.S. government acknowledged that Newtok needed to be relocated, but only three years ago did the Yup’ik finally receive \$15 million in aid, only a fraction of what will be required to relocate the entire village to safer ground.

In contrast, the Norwegian government has increased spending on the archipelago by 80 percent over the past five years. In 2018 it allotted a separate \$25.9 million for protective measures such as fencing to prevent snow from accumulating in avalanche-prone areas above Longyearbyen and to build new residential and student housing.

The government also earmarked almost \$12 million for up-

grades to the famous Svalbard Global Seed Vault, which flooded in 2017 from thawing permafrost and heavy rains. When I drove by it one morning on the way out of town, bulldozers cluttered the entrance to the vault. Norway is investing in the territory so its citizens will continue to live there despite the changing environment.

Longyearbyen can engineer defenses against climate-related threats to the land, to an extent. The community is relatively contained, compared with other parts of the Arctic, where permafrost underlies hundreds of kilometers of roads and pipelines. But the local government has to plan carefully. “There’s not a lot of space,” says Graham Gilbert, a geologist at the University Center in Svalbard, who studies geohazards and permafrost. Work can also be done to mitigate floods, landslides and avalanches, “but it’s very expensive,” Hisdal says.

HUMAN FLUX

LONGYEARBYEN’S POPULATION has grown somewhat slowly in the past decade, in part because of a housing squeeze, but its demographics have changed. Since 2008 the non-Norwegian population there has increased from 14 to 37 percent. Most transplants are from Europe and Asia and are looking for jobs in the burgeoning tourism industry, made more accessible because of climate change. Flights now arrive daily from Oslo.

Angie Magnaong, from the Philippines, had never heard of Svalbard and its visa-free access until her Norwegian boyfriend proposed they move there; she would have needed a visa to live on the mainland. The 24-year-old soon found a receptionist job at Gjestehuset 102—a former miners’ quarters converted into a

guesthouse in the avalanche risk “red” zone in a little neighborhood called Nybyen. She and two local Filipino friends chronicle their experiences on social media, she says, to show people back home their activities in “a place at the top of the world which is livable.”

Magnaong and others are moving there despite the permafrost and avalanche hazards because the economy is no longer geared toward men in the mining trade. During the coal era, workers and their families lived on the archipelago for years. But Norway’s government has been shutting down Norwegian coal mining, and this year it announced that the last coal-fired power plant would be closed in 2028 and replaced by one expected to burn natural gas or wood pellets. As miners have left, short-term residents have arrived.

Today about 30 percent of full-time jobs are in tourism, buoyed by visitors’ desire to see the Arctic before it is irrevocably changed, a trend called “Last Chance Tourism.” Prior to the coronavirus pandemic, local officials were becoming concerned with overtourism; in the summer, ice-free seas lured a cruise ship to the docks every few days. In 2019 Longyearbyen logged more than 150,000 “guest nights,” up from around 80,000 a decade ago. Between 2008 and 2015 hotels and restaurants grew from 11 to 18. The other big employer now is the state-run University Center, focused on Arctic sciences. Every year hundreds of students from a variety of countries arrive, but then they often leave within



ANGIE MAGNAONG stops outside Gjestehuset 102, the miners'-quarters-turned-hostel where she works. Svalbard has no visa requirement, and she came from the Philippines seeking adventure.

six months; visiting scientists do not stay very long, either.

The turnover has created what Norway's government calls a "revolving door society." Longyearbyen today "is not a place where people stay," says Rachel Tiller, a political scientist and researcher at SINTEF Ocean, who studies sovereignty issues on Svalbard. Most young newcomers leave within seven years—far greater turnover than in any municipality on the mainland. The growing lack of generational memory makes the community less cohesive and therefore less resilient to the environmental changes unfolding, Tiller thinks. Without such deep social ties, it can be hard for the community to band together in the face of adversity presented by avalanches and runaway warming. Leaving is the easier option.

FOLLOW THE FISH

MORE CHANGE might come from an unexpectedly growing industry. On a balmy day at the end of a July 2020 heat wave, Haakon Hop, a senior marine biologist at the Norwegian Polar Institute, boarded the RV *Kronprins Haakon*, a research icebreaker, and headed out into the protected waters of Kongsfjorden along Svalbard's western coast. Two glaciers were calving, sending bits of icebergs past the vessel. Hop had studied these waters for decades, watching walrus, bearded seals and belugas. The crew deployed their net to sample the fjord's fish, and when they hoisted it up, they found the biggest Atlantic cod Hop had ever seen—more than a meter long. The crew passed their catch around by the tail, posing for photographs like champion fishers.

The Atlantic cod is one of the most valuable fish species in the world, and "a greater proportion of the population is now situated around Svalbard than it used to be," Hop says. The fish are coming from the south to warming waters in the High North, and they are growing larger because the warmer water promotes growth spurts in larval and juvenile cod. Northeast Atlantic mackerel are arriving more frequently, too. For decades fishers from various countries along the old migration route negotiated shares of the mackerel take, but those talks broke down when the migration pattern changed.

The Svalbard Treaty gave signatory nations fishing rights in 12 nautical miles of territorial waters around the archipelago's shores. Because Svalbard was under its control, in 1976 Norway considered extending its own marine claim to 200 nautical miles, creating a so-called exclusive economic zone, which is commonly used by countries worldwide. This zone includes all rights to resources in the water and on and under the seafloor—the

continental shelf. Today Norway values its Svalbard fishing trade at about \$94 million annually.

Some countries took issue with Norway's idea, including the Soviet Union, whose officials believed the treaty made Svalbard's waters communal. To appease them, Norway decided to create a fisheries protection zone (FPZ) that reached out to 200 nautical miles. The FPZ gave environmental responsibility to Norway, and Norway allotted small fishing quotas only to certain countries that had historically fished the waters. "The FPZ solved the immediate problem," says Andreas Østhagen, a senior research fellow at the Fridtjof Nansen Institute. Everything seemed to be working fine until, as Østhagen puts it, "the stupid snow crab wandered in."



HIGH-DENSITY HOUSING and university dormitories are being built in anticipation of more jobs and greater workforce turnover. Steel fences (seen on mountainside) have been installed to thwart avalanches.

The snow crab, a commercially valuable crustacean, has been scuttling northward along the seafloor toward Svalbard as its native habitat warms. Because the crab lives on the bottom—not considered part of the water column—Norway banned the catch of snow crabs by foreign boats in 2014, not contradicting the FPZ, which applied only to the water column. The E.U. protested, but Russia did not seem concerned, because it still had plenty of crabs on its own seafloor.

Russia, however, is eyeing oil and gas deposits under Svalbard's continental shelf. Surveyors estimate that the equivalent of 1.4 billion cubic meters of oil could lie in the vicinity of Svalbard. "If Norway accepted the E.U. position [on crabs], it would create a precedent" for seafloor access to oil and gas by other countries, Østhaugen says.

Russia hopes to gain a greater foothold in Svalbard's tourism economy as well. Nine years ago Grete K. Hovelsrud, an envi-

ronmental sociologist at Nord University in Bodø and at the Nordland Research Institute, traveled with a small group of climate scientists to Barentsburg, the Russian mining settlement 60 kilometers southwest of Longyearbyen along the ocean's edge. When they pulled up in a boat, a young Russian man was waiting on the dock to greet them. "It was like a ghost town," Hovelsrud says. The man led the group past the wood Russian Orthodox church and into a hotel that housed the town's lone cafe and restaurant. The dining room had 20 tables but only one place setting—for the man. "He was so upbeat," she recalls. He talked about how warm it had been and said he was hopeful more people would come.

About 30 percent of jobs are in hospitality, buoyed by visitors' desire to see the Arctic before it is irrevocably changed, a trend called "Last Chance Tourism."

They have. Barentsburg now has two hotels and a brewery. The Russians want to have more of a presence in Svalbard, Hovelsrud says. With coal on the way out, being part of the tourism trade is part of Russia's larger Arctic strategy, she says. Russia has said it also intends to build a facility in Barentsburg to process fish for export to distant markets. Perhaps in response to a coming scramble for resources in Svalbard, Norway's government has announced it will open a Longyearbyen office of the Ministry of Trade, Fisheries and Industry—the first time a ministry has opened an office outside of Oslo.

INCONGRUOUS PATHS

THE GEOPOLITICAL POSTURING is unsettling for longtime residents because the Arctic has historically been a peaceable region. Hovelsrud first visited Longyearbyen in the 1980s during the cold war to study reindeer. Everyone knew who the KGB agent was in town, she says. He would sit at the bar in Huset, the min-

ers' hall, and casually snap pictures of other imbibers, who did not care. On weekends, Russians and Norwegians met by snowmobile on one of the glaciers to exchange goods. "I would [trade] jeans [for] boots and bearskin hats," Hovelsrud laughs. Despite global friction between the Soviet Union and the West, local relations were at ease. Hovelsrud says this is still the case among residents, but in international relations, "something has shifted. There is a general tension toward the Arctic and the resources up there." Svalbard has become strategic real estate, too. When NATO held a 2017 parliamentary assembly meeting in Svalbard, Russia called the maneuver "provocative." A 2020 Norwegian Intelligence Service report warned that Russian operators were using online misinformation in attempts to sow discord between Norway's northernmost communities and the national government in Oslo.

Bjørn P. Kaltenborn, a human geographer at the Norwegian Institute for Nature Research, who studies how Longyearbyen residents are coping with climate change, thinks more nations, particularly China, "will be pushing to have more access to logistics and resources." Already China has established the Yellow River Research Station in the remote scientific enclave of Ny-Ålesund, 180 kilometers northwest of Longyearbyen. And this past March, China confirmed its plan to construct a "polar silk road"—a network of investments in Arctic oil, gas, mining and shipping. Because of the nondiscrimination principle, there is not much the Norwegian government can

do about investment from people around the world. This "unpredictable power game" over resources will "clearly affect the community of Longyearbyen and its economic, social and cultural development," according to a 2019 study co-authored by Kaltenborn, Hovelsrud and Julia Olsen of the Nordland Research Institute. People there are "starting to worry" about their way of life, Kaltenborn tells me. Thawing permafrost, avalanches, ships filled with tourists and competition among global powers—all amplified by warming—will certainly affect the social climate. The only question is: How?

For now any geopolitical drama does not seem to have altered daily life in Longyearbyen. Sabbatini acknowledged the stressors when I recently talked with him, but when I asked about rising tension, he was a bit flippant. "Svalbard has become this massive target, in large part because it's so open. Sure, it's fun to read that we'd get [overwhelmed] by the Russians if they rolled in here," he chuckles. "But what are the chances that's going to happen?"

Running a local newspaper, he is not naive about change. But maybe he prefers to focus on Svalbard's unique, natural beauty. "The Northern Lights this year," he says, "have just been fantastic." ■

FROM OUR ARCHIVES

Perma-Vault Now Accepting Seeds. Melinda Wenner; Scientific American Earth 3.0, September 2008.

[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)

BIOLOGY

BROOD RISING

After 17 years underground, the Great Eastern Brood of periodical cicadas is emerging

Text by Kate Wong and Illustrations by Cherie Sinnen

AT THIS VERY INSTANT, IN BACKYARDS AND FORESTS ACROSS THE EASTERN U.S., ONE OF NATURE'S GREATEST spectacles is underway. Although it may lack the epic majesty of the wildebeest migration in the Serengeti or the serene beauty of cherry blossom season in Japan, this event is no less awe-inspiring. I'm talking about the emergence of the Brood X cicadas.

Every 17 years the billions of constituents of Brood X tunnel up from their subterranean lairs to spend their final days partying in the sun. This generation got its start back in 2004, when Facebook existed only at Harvard University and *Friends* aired its last episode. The newly hatched cicada nymphs fell from the trees and burrowed into the dirt. They have been underground ever since, feeding on sap from the rootlets of grasses and trees and slowly maturing. All of that preparation has been leading up to this moment when they surface in droves—up to 1.4 million cicadas per acre—to molt into their adult form, sing their deafening love song and produce the next generation before dying just a few weeks later.

To early European settlers in North America, the sudden ap-

pearance of these insects in large numbers brought to mind the locusts of biblical infamy. But whereas locusts are grasshoppers that form giant swarms and travel long distances, devouring crops on a devastating scale, cicadas belong to an entirely different order of insects. They do not swarm and are poor fliers, typically traveling no more than several hundred feet. Moreover, they pose little threat to plants because they do not eat plant tissues. Females do make incisions in twigs for their eggs, which can weaken saplings but not mature trees and shrubs.

Nearly 3,400 species of cicadas exist worldwide. But periodical cicadas that emerge en masse once every 17 or 13 years are unique to the eastern U.S. The 17-year cicadas live in the North, and the 13-year cicadas are found in the South and the Mississip-

WILLIAM S. KILTA/Alamy Stock Photo



pi Valley. The three species of 17-year cicadas—*Magicalcanda septendecim*, *M. cassinii* and *M. septendecula*—form mixed-species cohorts called broods whose members arise like clockwork on the same schedule. The

broods are identified by Roman numerals. Brood X is the largest of the 12 broods of 17-year cicadas, which emerge in different years.

The periodical life cycles of these cicadas, with their long developmental phases and synchronized emergences, have long captivated scientists. Most other cicadas studied thus far have life cycles of three to five years, says Chris Simon of the University of Connecticut. Their nymphs grow at different rates depending on genetic and environmental factors, and they stage their exit from underground once they reach a certain body size and level of development. As a result, the offspring of any one female come out in different years, she explains. Periodical cicadas, in contrast, stay belowground for a fixed amount of time, regardless of when they reach full size, and then emerge together.

Exactly how periodical cicadas came to have these unique life history patterns is an area of active research. DNA analyses suggest an approximate time line of their evolution. The last common ancestor of all living *Magicalcanda* species branched into two lineages around 3.9 million years ago during the Pliocene epoch. One of these branches itself diverged 1.5 million years later during the Pleistocene. The three resulting lineages ultimately gave rise to the seven species of 13- and 17-year cicadas alive today. Why these cicadas settled on 13- and 17-year sched-

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Cherie Sinnen is a freelance illustrator based in California.



ules is unknown. One hypothesis holds that having long, prime-number cycles might boost their odds of survival by offsetting their emergence from predator-population booms that occur more frequently and on composite-number cycles. But the two other known periodical cicadas—one in Fiji and the other in India—emerge at eight- and four-year intervals, respectively.

Researchers have proposed that periodical cicadas evolved from nonperiodical cicadas by trading a size-based emergence schedule for an age-based one and extending the development period. Climate change probably helped drive this shift. Periodical cicadas are sensitive to temperature—it determines the length of the growing season. During the Pleistocene, cooling temperatures would have slowed juvenile development on average but increased the variation in the growth period, making the timing of adult emergence in ancestral cicadas even more variable than before. With the resulting reduction in the density of adult cicadas emerging in any given year, mating opportunities would have

Some six to 10 weeks after female cicadas lay their eggs in the trees, tiny cicada nymphs hatch and drop to the ground where they burrow into the soil.

They sip fluids from grass roots at first, then dig down eight to 12 inches to feed on sap from tree roots.

Born in July and August, cicadas start out as pale, antlike nymphs just a tenth of an inch long.

Late Bloomers

Periodical cicadas take longer than any other insect to develop from egg to adult. They spend most of their lives underground feeding and growing and then emerge together after a fixed amount of time. Their synchronous emergence in large numbers ensures that, even after predators eat their fill, plenty of cicadas remain to mate and reproduce. Studies suggest that the cicadas track the passage of time by monitoring seasonal fluctuations in the tree sap they feed on. But how they remember how many years have passed—and what triggers them to surface—remains unknown.

They pass through five developmental stages called instars. By about 12 to 13 years of age, the developing cicada has reached its fifth and final nymphal stage.

In May, just a few months before their 17th birthday, the nymphs exit from a hole in the ground. Initially more males than females emerge; after six days more females than males emerge.

In April of their 16th year, they tunnel up to about four to six inches underneath the surface and wait.



Once the exoskeleton hardens (about five days later), males start singing. Loudly.

Within about an hour of emerging from the ground, the cicada sheds its nymphal skin and enters into adulthood. Initially the new adults appear mostly white, but they darken quickly as the exoskeleton hardens. Empty skins can remain attached to vertical surfaces or drop to the ground.

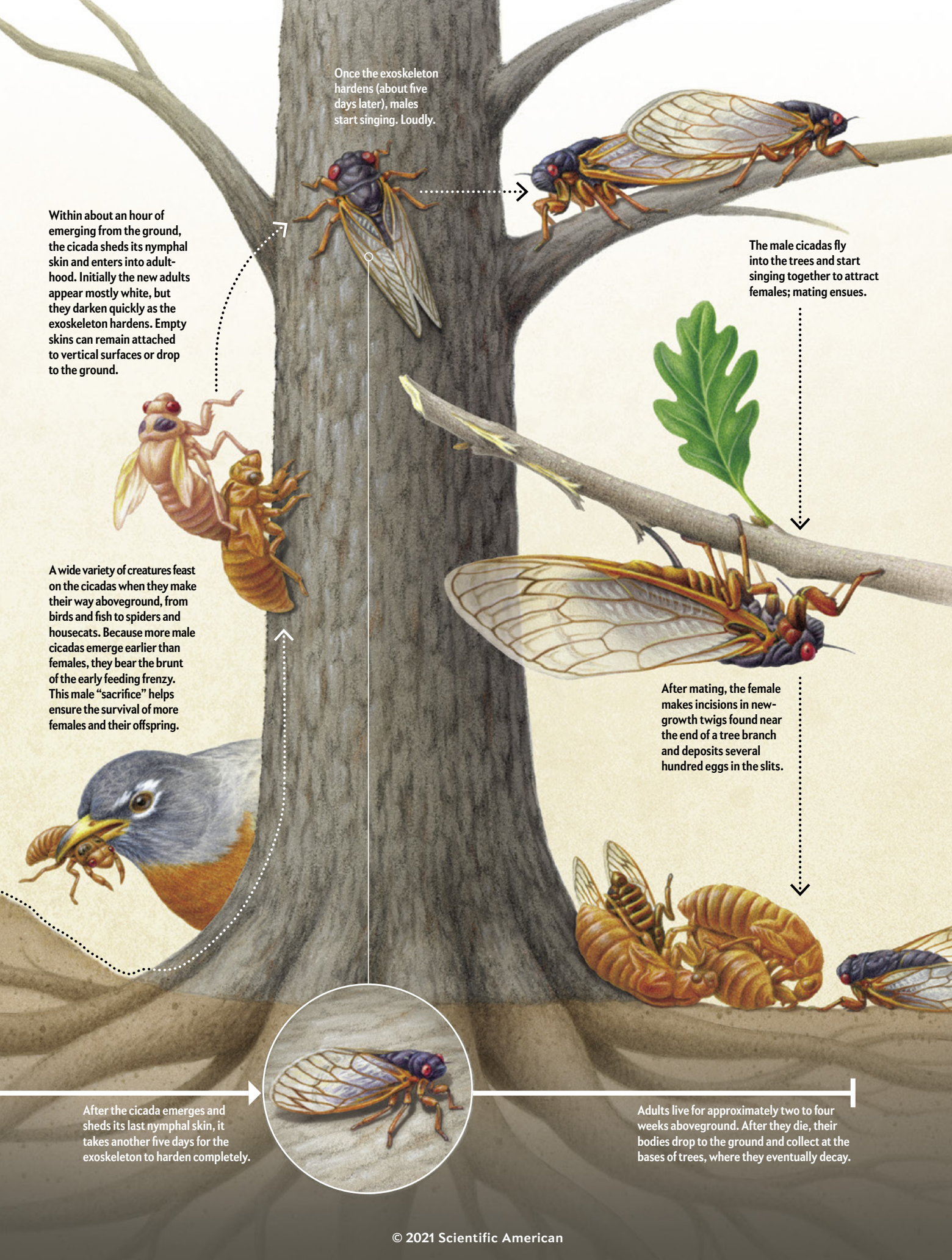
A wide variety of creatures feast on the cicadas when they make their way aboveground, from birds and fish to spiders and housecats. Because more male cicadas emerge earlier than females, they bear the brunt of the early feeding frenzy. This male "sacrifice" helps ensure the survival of more females and their offspring.

The male cicadas fly into the trees and start singing together to attract females; mating ensues.

After mating, the female makes incisions in new-growth twigs found near the end of a tree branch and deposits several hundred eggs in the slits.

After the cicada emerges and sheds its last nymphal skin, it takes another five days for the exoskeleton to harden completely.

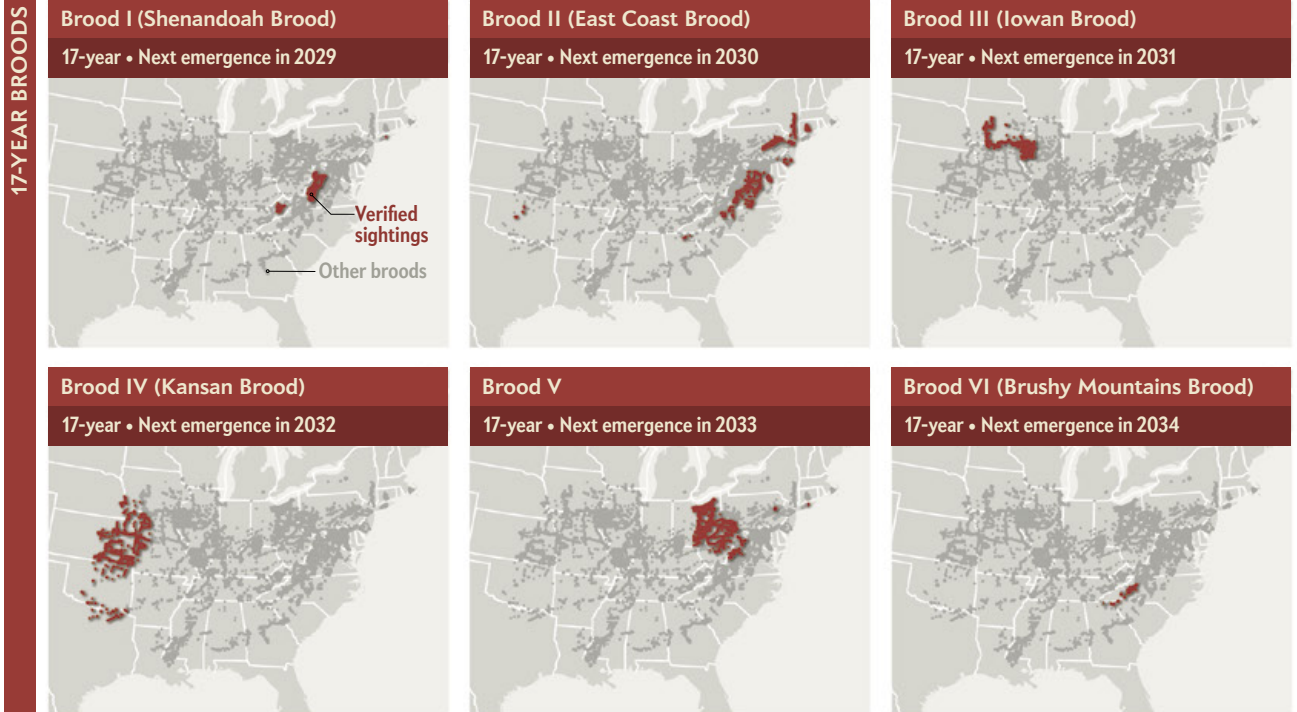
Adults live for approximately two to four weeks aboveground. After they die, their bodies drop to the ground and collect at the bases of trees, where they eventually decay.



Broods and Species

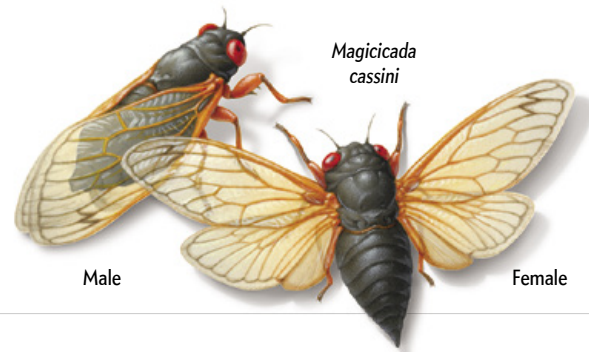
Periodical cicadas that emerge every 13 or 17 years are unique to the eastern U.S. There are three species of 17-year cicadas and four species of 13-year cicadas. All the cicadas of the same life cycle that live in the same region and emerge in the same year are said to belong to a single cohort called a brood. There are 12 broods of 17-year cicadas and three broods of 13-year cicadas.

Each brood has been assigned a roman numeral. Climate change over the past 20,000 years, combined with the periodical cicadas' ability to temporarily shift their life cycle to emerge four years early if conditions are favorable or four years late if they are difficult, is thought to have driven the formation of the broods, whose ranges fit together like the pieces of a jigsaw puzzle.



Members of Brood X

The three 17-year cicada species—*Magicicada cassini*, *Magicicada septendecula* and *Magicicada septendecim*—all appear broadly similar with their red eyes, black bodies and orange wing veins. But they differ in details of their size, shape, color and song. *M. septendecim* is the largest, for instance, whereas *M. septendecula* has thin orange stripes on the underside of its abdomen, and *M. cassini* has a song consisting of ticks followed by a shrill buzz. Each 17-year species has at least one 13-year counterpart that is physically and behaviorally similar to it (*not shown*).

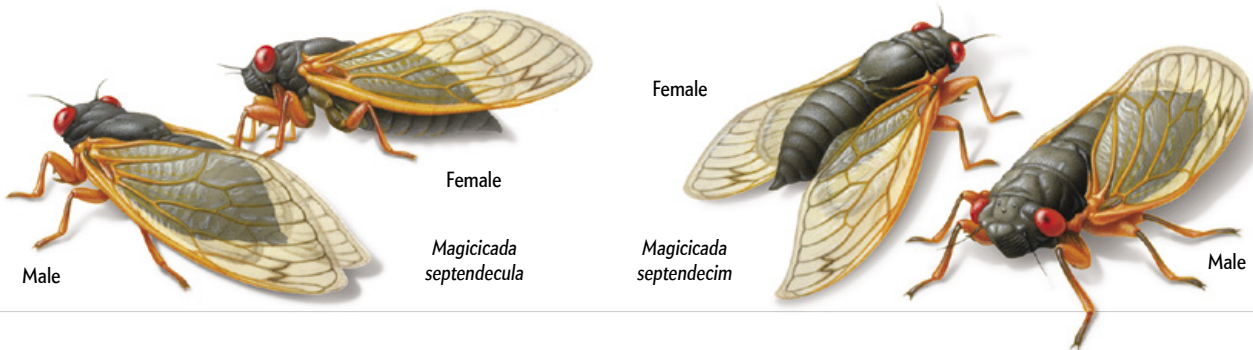
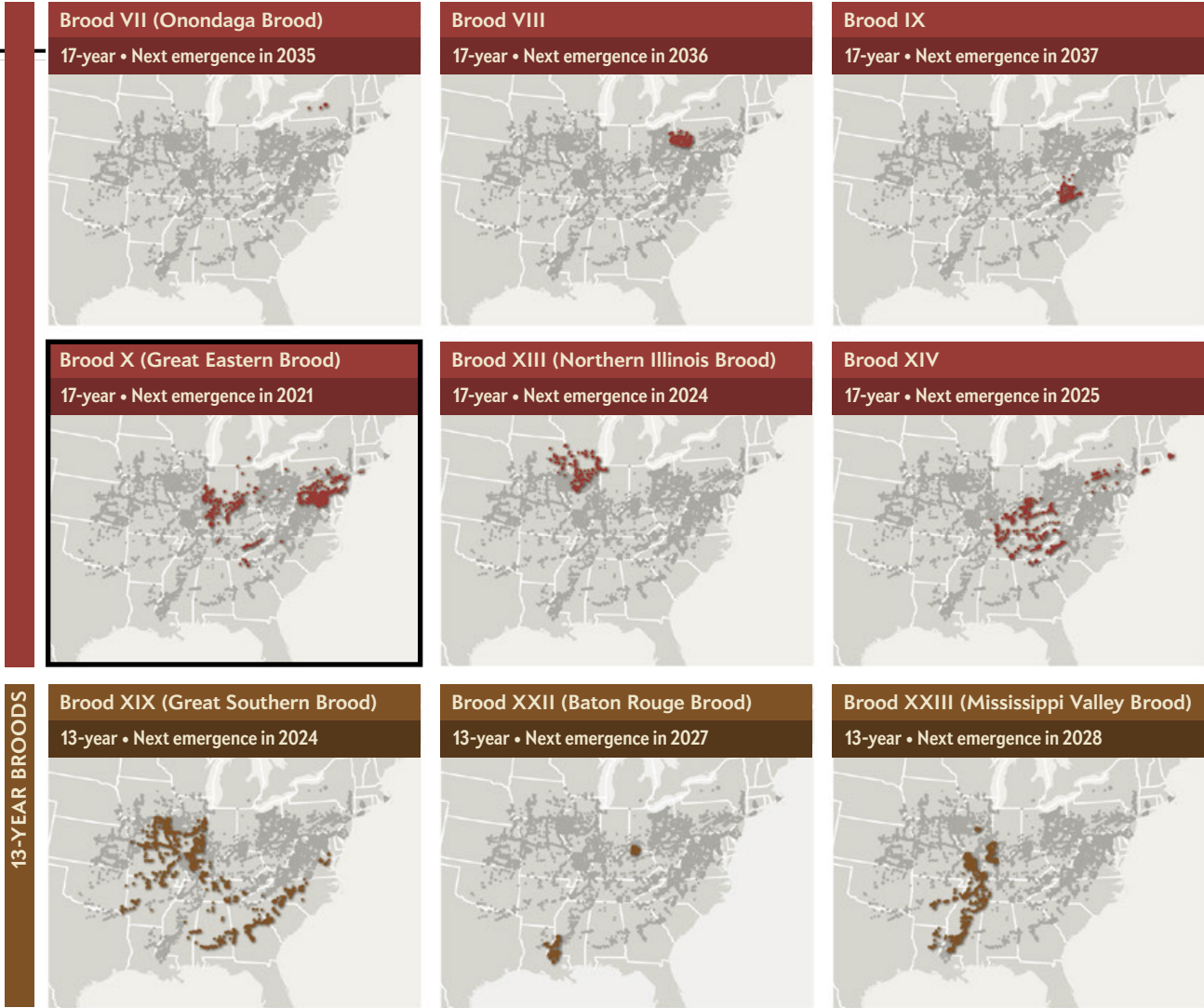


dwindled. Under such conditions, switching from a size-based emergence strategy to an age-based one in which the insects remain underground for a long time and then surface simultaneously would increase the adult population density at emergence and thus their opportunities to find mates and reproduce.

Emerging simultaneously in huge numbers also overwhelms predators. Consequently, even after the birds, mammals and fish have satiated themselves on the plump, defenseless insects, plenty of cicadas remain to produce the next generation.

Climate change also shaped the distribution of the broods. As North America's ice sheets advanced and retreated over the past 20,000 years, the deciduous forests that cicadas inhabit shrank

and expanded. Broods evolved in response to those cooling-warming cycles. Gene Kritsky of Mount St. Joseph University in Cincinnati, Ohio, points to Brood X in the western part of his state as an example. Twenty thousand years ago the ice sheets extended to just north of where Cincinnati is today. Because the land was covered in ice, there were no forests, and thus no cicadas, in western Ohio back then. Around 14,000 years ago, however, the ice sheet retreated north. "Forests came in, and periodical cicadas came with them," Kritsky explains. Ohio hosts three other 17-year cicada broods, each of which occupies its own region of the state. "The distribution in Ohio of 17-year cicadas matches the physiographic regions created by the ice ages," he observes.



Periodical cicadas have been able to adapt to climate change in part because they have some plasticity in their life-cycle length: they can accelerate or decelerate their emergence schedules by four-year increments. But this flexibility does not assure their long-term survival. Brood XI has been extinct since around 1954; others are waning. The main threat is habitat loss, according to Kritsky. In 1919 the U.S. Department of Agriculture predicted the demise of Brood X as a result of deforestation.

Mapping periodical cicada emergences helps scientists gauge how the broods are faring. Researchers have asked the public to report sightings for decades—in the old days via postcard and later by phone and e-mail. Now they are crowdsourcing data with

an app that Kritsky and his colleagues developed, called Cicada Safari, that allows people to submit pictures and videos of any cicadas they encounter and view a map of the Brood X emergence in real time as it unfolds. “In 1902 the USDA based its map on just under 1,000 postcards it received,” Kritsky says. This year, through the app, “we’re hoping to get 50,000 photographs.” A fitting send-off for the Brood X class of 2021. **SA**

FROM OUR ARCHIVES

How Cicadas Make Their Noise. Henry C. Bennet-Clark; May 1998.

[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)



SUSTAINABILITY

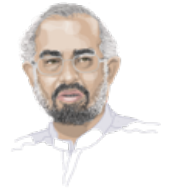
A TAPESTRY OF ALTERNATIVES

Making peace with the biosphere will require building communities and relationships that are focused on sustaining life—human and nonhuman

Text and photographs by Ashish Kothari

INDIGENOUS SEEDS, nourished by rainwater and organic supplements, help Nadimidoddi Vinodamma of the Deccan Development Society (DDS), a farmers' cooperative in southern India, grow enough food for her family as well as to sell in local markets.

Ashish Kothari is a founding member of Kalpavriksh, an environmental organization in India. He helps coordinate the *Global Tapestry of Alternatives* and has co-authored or co-edited several books, including *Churning the Earth* (2012) and *Pluriverse* (2019).



N O ONE IN HER VILLAGE FACED FOOD SHORTAGES DURING THE LOCKDOWNS, nor did they suffer from COVID-19, Moligeri Chandramma assured me through an interpreter this past March. A farmer in the drylands of southern India, she grows more than 40 species and varieties of crops—mostly native millets, rice, lentils and spices—on a bit more than a hectare of land. Chandramma is a member of the Deccan Development Society (DDS), a cooperative of nearly 5,000 Dalit (oppressed caste) and Adivasi (Indigenous) women whose remarkable integration of biodiversity conservation with agricultural livelihoods earned them the United Nations’ prestigious Equator Award in 2019. Emerging from a situation of extreme malnutrition and social and gender discrimination in the 1980s, these farmers now enjoy food sovereignty and economic security. Not only are they weathering the pandemic, in 2020 each family in DDS contributed around 10 kilograms of food grains to the region’s relief effort for those without land and livelihoods.

On the other side of the world, six Indigenous Quechua communities of the Peruvian Andes govern the Parque de la Papa (Potato Park) in Pisac, Cusco, a mountainous landscape that is one of the original homelands of the potato. They protect the region as a “biocultural heritage” territory, a trove of biological and cultural riches inherited from ancestors, and conserve more than 1,300 varieties of potato. When I visited in 2008 with other researchers and activists, I was stunned into silence by the diversity.

“This is the outcome of 20 years’ consistent work in relocalizing our food system, from a time when we had become too dependent on outside agencies for our basic needs,” farmer Mariano Sutta Apocusi told *Local Futures*, an organization dedicated to strengthening communities worldwide, in August 2020. “Focusing on the local has helped us improve access to and affordability of a great diversity of food products—especially native potatoes, quinoa, kiwicha, other Andean tubers and maize, which we cultivate using Indigenous agroecological methods.” The communities instituted strong health and safety measures when the pandemic hit, even as they harvested a bumper crop and distributed more than a ton of potatoes to migrants, the elderly and a shelter for abused teenage mothers in Cusco town.



In Europe, many “solidarity economy” initiatives, which promote a culture of caring and sharing, swung into action when COVID-related lockdowns rendered massive numbers of people jobless. In Lisbon, Portugal, the social centers Disgraça and RDA69, which strive to re-create community life in an otherwise highly fragmented urban situation, reached out with free or cheap food to whoever needed it. They provided not only meals but also spaces where refugees, the homeless, unemployed young people and others who might otherwise have fallen through the cracks could interact with and develop relationships with better-off families, creating a social-security network of sorts. The organizers trusted those with adequate means to donate food or funds to the effort, strengthening the feeling of community in surrounding neighborhoods.



MOLIGERI CHANDRAMMA manages the DDS seed bank (1). It contains more than 70 species and varieties of crops. People gathered (2) in 2005 to mark 20 years of sustained protests against dam construction on the Narmada River.

The pandemic has exposed the brittleness of a globalized economy that is advertised as benefiting everyone but in fact creates deep inequalities and insecurities. In India alone, 75 million people fell below the poverty line in 2020; globally, hundreds of millions who depend for their survival and livelihoods on the long-distance trade and exchange of goods and services were badly hit. Similar, albeit less extreme, dislocations also appeared during the 2008 financial crisis, when commodity speculation, along with the diversion of food grains to biofuel production, precipitated a steep rise in global grain prices, leading to hunger and food riots in many countries that depended on imported food. Threats to survival also emerge when war or other dislocations stop the movement of goods. In such crises, communities fare better if they have local markets and services and can provide their own food, energy and water while taking care of the less fortunate.

The value of these alternative ways of living goes far beyond their resilience during relatively short-term upheavals like the pandemic, however. As a researcher and environmental activist based in a “developing” country, I have long advocated that the worldviews of peoples who live close to nature be incorporated into global strategies for wildlife protection, such as at the [International Union for Conservation of Nature](#) and the [United Nations’ Convention on Biological Diversity](#). And in recent decades I have

come to agree with [critics of globalization](#) such as social scientist and environmentalist Wolfgang Sachs that fending off calamities like biodiversity collapse will require not only environmental adaptations but also radical changes to the dominant economic, social and even political paradigms.

In 2014 a few of us in India initiated a process to explore pathways to a world in which people are at peace with one another and with nature. Five years later (and fortuitously, just before the pandemic hit), the endeavor grew into an [international online network](#) we called the [Global Tapestry of Alternatives](#). These conversations and other research indicate that viable options, no matter where they are, tend to be based on self-reliance and solidarity.

Such values are at odds with globalization, which delivers to denizens of the Global North (the better off, no matter where we live) many things that we have come to regard as essential. In contrast to the promise of ever increasing material wealth that underpins our civilization, peoples who live near or beyond its margins have a multitude of visions for living well, each tailored to the specifics of their ecosystems and cultures. To walk away from the cliff edge of irreversible destabilization of the biosphere, I believe we must enable alternative structures, such as those of the Dalit farmers, the Quechua conservers and the Lisbon volunteers, to flourish and link up into a tapestry that ultimately covers the globe.

AN ENLIGHTENING JOURNEY

GROWING UP IN INDIA, where lifestyles that are [intimately entwined](#) with the natural environment survive in large pockets, unquestionably influenced my ideas of what constitutes true sustainability. In the 1970s, as a high school student who loved bird-watch-



1

ing in forests around Delhi, I joined classmates to demonstrate outside the Saudi Arabian embassy when some princes arrived in the country to hunt the (now critically endangered) Great Indian Bustard. Our protest, along with that of the Bishnoi community in Rajasthan, which traditionally protects these birds and other wildlife, embarrassed the Indian government into requesting that the hunters go home. Many of us went on to campaign for protection of the Delhi Ridge Forest, one of the world's biggest urban jungles. In 1979 we formed an environmental group to systematize our efforts. We called it Kalpavriksh, after a mythical tree that makes wishes come true; the name symbolized our growing awareness that nature gives us everything.

Our activism would teach us at least as much as we learned in school and college. While investigating the sources of Delhi's air pollution, for instance, we interviewed villagers who lived around a coal-fired power plant just outside the city. They turned out to be far worse affected by its dust and pollution than we city dwellers were—although they got none of its electricity. The benefits of the project flowed mainly to those who were already better off, whereas the disempowered experienced most of the harms.

In late 1980 we traveled to the western Himalayans to meet the protagonists of the iconic Chipko movement. Since 1973 village women had been protecting trees slated for logging by the forest department or by companies based in the Indian plains with their bodies. The deodars being felled, as well as the oaks, rhododendrons, and other species, were sacred, the women told us, as well as being essential for their survival. They provided cattle fodder, fertilizer and wild foods and sustained their water

sources. Even as an urban student, I could see the central role that rural women played in protecting the environment—as well as the injustice of distant bureaucrats making decisions with little concern for how they impacted those on the ground.

Soon after, my friends and I learned that 30 major dams were to be constructed on the Narmada River basin in central India. Millions worshipped the Narmada as a tempestuous but bountiful goddess—so pristine that the Ganga is believed to visit her every year to wash away her sins. Trekking, boating and riding buses along its length of 1,300 kilometers, we were dazzled by waterfalls plunging into spectacular gorges, densely forested slopes teeming with wildlife, fields of diverse crops, thriving villages and ancient temples, all of which would be drowned. We began to question the concept of development itself. Surely the destruction would far outweigh any possible benefits? Almost four decades later our fears have proved tragically true. Hundreds of thousands of displaced people still await proper rehabilitation, and the river downstream of the dams has become a trickle—enabling seawater to reach 100 kilometers inland.

Over the years I came to understand how powerful economic forces reach around the globe to intimately link social injustice with ecological destruction. The era of colonization and slavery vastly expanded the economic and military reach of some nation-states and their allied corporations, enabling the worldwide extraction of natural resources and exploitation of labor to feed the emerging industrial revolution in Europe and North America. Economic historians, anthropologists and others have demonstrated how this painful history laid the foundation of today's



PARQUE DE LA PAPA (1) in Peru is one of the original homelands of the potato. The Quechua Indigenous people (2) govern the region as a “biocultural heritage” territory, conserving a remarkable diversity of potatoes (3).

global economy. Apart from driving irreversible ecological damage, this economic system robs many communities of access to the commons—to rivers, meadows and forests essential for their survival—while creating a dependence on external markets. The massive suffering during the pandemic has merely exposed these historical and contemporary fault lines.

During my wanderings over the decades and especially while researching a [book](#) with economist Aseem Shrivastava, I became aware of a far more hopeful trend. Across the country and indeed around the world, hundreds of social movements are empowering the marginalized to wrest back control over their lives and livelihoods. In 2014 Kalpavriksh initiated a series of gatherings called [Vikalp Sangam](#), or Confluence of Alternatives, where the drivers of these spirited efforts could come together, share ideas and experiences, and collaborate, helping to build a critical mass for change.

These interactions and eclectic reading gave me insights into a vital question I was investigating: What are the essential characteristics of desirable and viable alternatives? Happily, I was far from alone in this quest. At a degrowth conference in Leipzig in 2014, I was excited to hear Alberto Acosta, an economist and former politician from Ecuador, speaking on *buen vivir*, an Indigenous worldview founded on living well with one another and with the rest of nature. Although Acosta spoke no English and I spoke no Spanish, we tried excitedly to converse; subsequently, [degrowth](#) expert Federico Demario joined us and helped to translate. We decided to work on a compilation of thriving alternatives from around the world—jotting down 20 possible ideas on the back of an envelope. Later we roped in development critic Arturo Escobar and ecofeminist Ariel Salleh as co-editors of a volume we called [Pluriverse](#). The number of entries expanded to more than 100.

COMMONALITIES

THOUGH DAZZLINGLY DIVERSE, the alternatives emerging worldwide share certain core principles. The most important is sustaining or

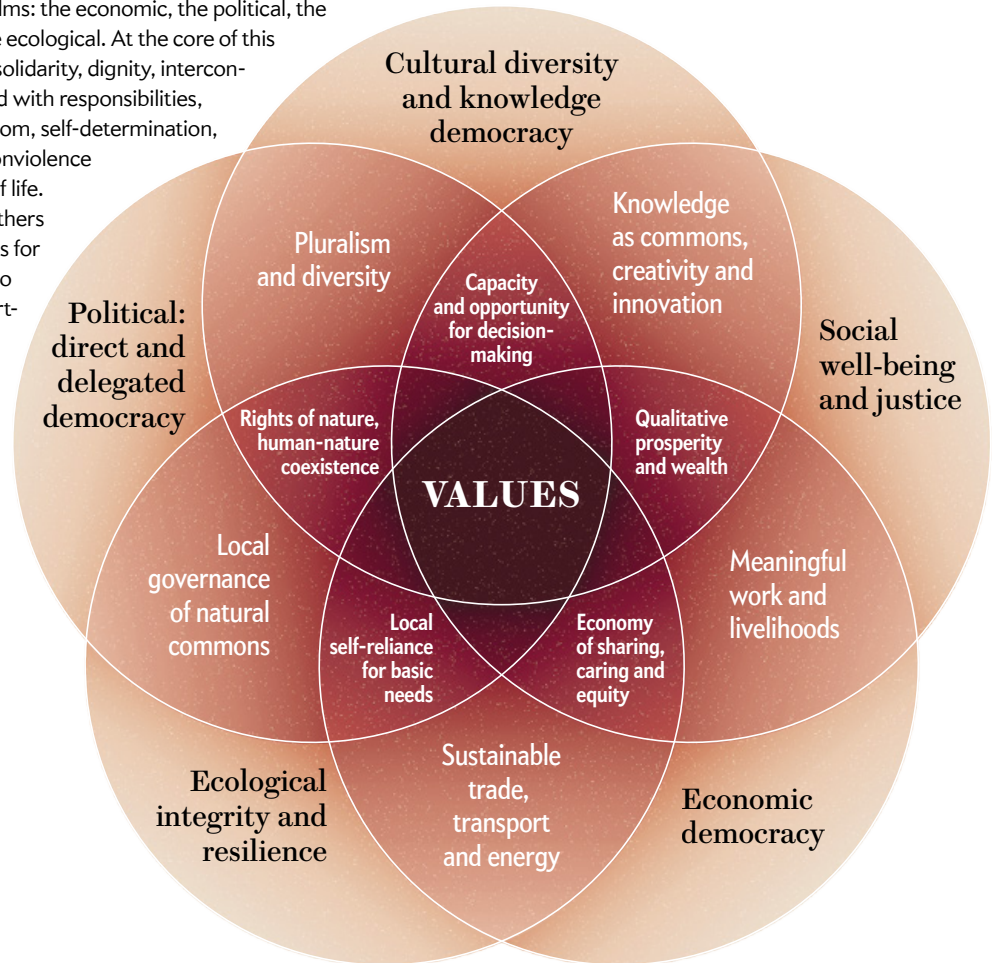


reviving community governance of the commons—of land, ecosystems, seeds, water and knowledge. In 12th-century England, powerful people began fencing off, or “enclosing,” fields, meadows, forests and streams that had hitherto been used by all. Enclosures by landlords and industrialists expanded to Europe and accelerated with the industrial revolution, forcing tens of millions of dispossessed people to either become factory workers or emigrate to the New World, devastating native populations. Imperial nations seized large portions of continents and reconfigured the economies of the colonies, extracting raw materials for factories, capturing markets for exports of manufactured goods and obtaining foods such as wheat, sugar and tea for the newly created working class. In this way, colonizers and their allies established a system of perpetual economic domination that generated the Global North and the Global South (the world of the marginalized, no matter where they live).

The wave of anticolonial movements in the first few decades of the 20th century, many of them successful, sparked fears that supplies of raw materials for industries and markets for finished goods of higher value would dry up. President Harry S. Truman responded by launching a program for alleviating poverty in what he described as “underdeveloped areas” with their “primitive and stagnant” economies. As [detailed](#) by ecologist Debal Deb, newly formed financial institutions controlled by the rich countries helped the ex-colonies “develop” along the path blazed by the West, providing the materials and energy sources for and creating markets for cars, refrigerators and other consumer goods. An integral aspect of development, as thus conceived, propagated and usually enforced by stringent conditions attached to loans from the World Bank and

Spheres of Transformation

Creating a sustainable and equitable world will require metamorphoses in five intersecting realms: the economic, the political, the social, the cultural and the ecological. At the core of this flower are values such as solidarity, dignity, interconnectedness, rights coupled with responsibilities, diversity, autonomy, freedom, self-determination, self-reliance, simplicity, nonviolence and respect for all forms of life. Indigenous peoples and others have lived by similar values for centuries, and they are also being embraced and asserted by people in industrial societies as solutions to global ecological and social crises.



the International Monetary Fund, has been privatization or state confiscation of the commons to extract metals, oil and water.

As Elinor Ostrom, winner of the 2009 Nobel Memorial Prize in Economic Sciences, demonstrated, however, the commons are far more sustainably governed by the communities from which they are wrested than by the governments or corporations that claim them. This awareness has given rise to innumerable grassroots efforts to protect the surviving commons and reestablish control over others. What constitutes the commons has also expanded to include “physical and knowledge resources that we all share for everyone’s benefit,” explains sociologist Ana Margarida Esteves, who helps with the European Commons Assembly, an umbrella organization for hundreds of such endeavors.

Many of the efforts resemble the DDS and the Parque de la Papa in using community governance of commonly held resources to enhance agroecology (smallholder farming that sustains soil, water and biodiversity) and food sovereignty (control over all means of food production, including land, soil, seeds and the knowledge of how to use them). The food-sovereignty movement

La Via Campesina, which originated in Brazil in 1993, now includes about 200 million farmers in 81 countries. Such attempts at self-reliance and community governance extend also to other basic needs, such as for energy and water. In Costa Rica, Spain and Italy, rural cooperatives have been generating electricity locally and controlling its distribution since the 1990s. And hundreds of villages in western India have moved toward “water democracy,” based on decentralized harvesting of water and community management of wetlands and groundwater. Mobilizing people to sustain, build or rebuild local systems of knowledge is essential to such ventures.

Secure rights to govern the commons are also important. In the Ecuadorian Amazon, the Sapara Indigenous people fought hard to gain collective rights over their rain-forest home. They are now defending it against oil and mining interests while developing a model of economic well-being that blends their traditional cosmovisions—ways of knowing, being and doing that are physically and spiritually linked to their environs—with new activities such as community-led ecotourism. Their income from

SOURCE: “ALTERNATIVES TRANSFORMATION FORMATA: A PROCESS FOR SELF-ASSESSMENT AND FACILITATION TOWARDS RADICAL CHANGE.” PREPARED BY KALPAKRISH FOR ACKNOWLEDGE (chart reference)

tourism has dropped during the pandemic, but their forests and community ethic give them almost all the food, water, energy, housing, medicines, enjoyment, health and learning that they need. They are now offering online sessions on their cosmovisions, dream analysis and healing. I participated in such sessions in person in their Naku ecotourism camp in 2019. The virtual version is not as immersive but nonetheless represents an innovative adaptation to the circumstances.

Greening cities or making them more welcoming, as the Lisbon social centers do, also requires community-based governance and economies of caring and sharing. Across the Global South, development projects have driven hundreds of millions of people to cities, where they live in slums and work in hazardous conditions. Wealthy city dwellers could do their part by consuming less, which would reduce the extraction and waste dumping that displace people in faraway places. A spectrum of avenues toward more equitable and sustainable cities has emerged. These include, for example, the Transition Movement, which is attempting to regenerate the commons and make European cities carbon-neutral, and the municipalism movement, which is creating a network of Fearless Cities, among them Barcelona, Valparaiso, Madrid and Athens, to provide secure environments for refugees and migrants. Urban agriculture in Havana supplies more than half of its fresh food requirements and has inspired many other city farming initiatives around the world.

FIVE PETALS

THESE INITIATIVES POINT TO the need for fundamental transformations in five interconnected realms. In the *economic sphere*, we need to get away from the development paradigm—including the notion that economic growth, as measured by gross domestic product (GDP), is the best means of achieving human goals. In its place, we need systems for respecting ecological limits, emphasizing well-being in all its dimensions and localizing exchanges to enable self-reliance—as well as good measures of these indicators. Bhutan has long experimented with gross national happiness as an index; the idea has spawned variants, such as New Zealand’s recent focus on mental health and other such measures of progress.

We also need freedom from centralized monetary and financial control. Many experiments in alternative currencies and economies based on trust and local exchanges are underway. Perhaps the most innovative of these is “time banking,” a system for swapping services founded on the principle that all skills or occupations merit equal respect. One can, for example, give a one-hour-long yoga lesson for

credit that can be redeemed for an hour’s work on bicycle repair.

In many parts of the world, workers are seeking to control the means of production: land, nature, knowledge and tools. A few years back I visited Vio.Me, a detergent factory in Thessaloniki, Greece, which workers had taken over and converted from chemical to olive-oil-based and eco-friendly production, and where they had established complete parity in pay, regardless of what job the worker was doing. The slogan on their wall proclaimed: “We have no boss!”

In fact, work itself is being redefined. Globalized modernity has created a chasm between work and leisure—which is why we wait desperately for the weekend! Many movements seek to bridge this gap, enabling greater enjoyment, creativity and satisfaction. In industrial countries, people are bringing back manual ways of making clothes, footwear or processed foods under banners such as “The future is handmade!” In western India, many young people are leaving soul-killing routines in factories to return to hand-



1



2

WORKERS such as Dimitris Koumatsioulis (1) collectively run Vio.Me, an eco-friendly detergent factory in Thessaloniki, Greece. In Prague, Czech Republic, people buy and sell locally (2) at a farmers’ and producers’ market.



loom weaving, which allows them to control their schedules while providing a creative outlet.

In the *political sphere*, the centralization of power inherent in the nation-state, whether democratic or authoritarian, disempowers many peoples. The Sapara nation in Ecuador and the Adivasis of central India argue for a more *direct democracy*, where power resides primarily with the community. The state—insofar as it continues to exist—would then mainly help with larger-scale coordination while being strictly accountable to decision-making units on the ground. The ancient Indian notion of *swaraj*, literally translated as “self-rule,” is particularly relevant here. It emphasizes individual and collective autonomy and freedom that are linked to responsibility for others’ autonomy and freedom. A community that practices *swaraj* may not dam a stream, for example, if that threatens the water supply of downstream villages; its well-being cannot compromise that of others.

Such a notion of democracy also challenges the boundaries of nation-states, many of which are products of colonial history and have ruptured ecologically and culturally contiguous areas. The Kurdish people, for instance, are split among Turkey, Iran, Iraq and Syria. For three decades they have struggled to achieve autonomy and direct democracy based on principles of ecological sustainability and *women’s liberation*—and without borders dividing them. And Indigenous groups in Mexico collectively identifying as Zapatistas have for more than three decades *asserted and sustained* an autonomous region based on similar principles.

Moving toward such radical democracy would suggest a world with far fewer borders, weaving tens of thousands of relatively autonomous and self-reliant communities into a tapestry of alternatives. These societies would connect with one another through “horizontal” networks of equitable and respectful exchange, as well

KUZGUNCUK BOSTAN, an urban commons in Istanbul, Turkey, enables city dwellers to collectively grow their own fruit, vegetables and other produce.

as through “vertical” but downwardly accountable institutions that manage processes and activities across the landscape.

Several experiments in bioregionalism at large scales are underway, although most remain somewhat top-down in their governance. In Australia, the *Great Eastern Ranges Initiative* seeks to coordinate the conservation of ecosystems across 3,600 kilometers while sustaining livelihoods and community health. And a project spanning six countries in the Andes aims to conserve as a World Heritage Site the Qhapaq Ñan, a 30,000-kilometer network of roads built by the Inca Empire, along with its related cultural, historical and environmental heritage.

Local self-governance may, of course, be oppressive or exclusionary. The intensely patriarchal and casteist traditional village councils in many parts of India and the xenophobic antirefugee approaches of the right wing in Europe illustrate this drawback. A third crucial sphere of transformation is therefore *social justice*, encompassing struggles against racism, casteism, patriarchy, and other traditional or modern forms of discrimination and exploitation. Fortunately, success in defying the dominant economic system often goes hand in hand with victories against discrimination, such as Dalit women farmers’ shaking off centuries of caste and patriarchal oppression to achieve food sovereignty.

Political autonomy and economic self-reliance need not mean isolationism and xenophobia. Rather cultural and material exchanges that maintain local self-reliance and respect ecological sustainability would replace present-day globalization—which per-

versely allows goods and finances to flow freely but stops desperate humans at borders. This kind of localization would be open to people in need; refugees from climate change or war would be welcomed, as in the network of Fearless Cities in Europe. Both grounded practice and shifts in policy could help transit toward such a system. Necessary, of course, are attempts to rebuild societies in regions of strife so that people do not have to flee from them.

Radical change also necessitates transformations in a fourth sphere: that of *culture and knowledge*. Globalization devalues languages, cultures and knowledge systems that do not adapt to development. Several movements are confronting this homogenizing tendency. The Sapara nation is trying to resuscitate its almost extinct language and preserve its knowledge of the forest by bringing these into the curriculum of the local school, for instance. Many communities are “decolonizing” maps, putting back their own place names and defying political borders. Even the colonial-era Mercator projection used to generate the familiar world map is being upended. (Only recently did I realize that Africa is large enough to contain Europe, China, the U.S. and India put together.) Increasingly, traditional and modern sciences are collaborating to help solve humankind’s most vexing problems. The Arctic Biodiversity Assessment, for example, involves cooperation among Indigenous peoples and university scientists to tackle climate change.

One problem is that present-day educational institutions train graduates who are equipped to serve and perpetuate the dominant economic system. People are bringing community and nature back into spaces of learning, however. These efforts include Forest Schools in many parts of Europe that provide children with hands-on learning in the midst of nature, the Zapatista autonomous schools that teach about diverse cultures and struggles, and the Ecoversities Alliance of centers of higher learning around the world that enable scholars to seek knowledge across the boundaries that typically separate academic disciplines.

The most important sphere of transformation, however, is the *ecological*—recognizing that we are part of nature and that other species are worthy of respect in their own right. Across the Global South, communities are leading efforts to regenerate degraded ecosystems and wildlife populations and conserve biodiversity. Tens of thousands of “territories of life” are being governed by Indigenous or other local communities, for example. These include locally managed marine areas in the South Pacific, Indigenous territories in Latin America and Australia, community forests in South Asia, and the Ancestral Domain territories in the Philippines. Also noteworthy is recent legislation or court judgments in several countries asserting that rivers, for example, enjoy the same protections as people. The United Nations’ 2009 Declaration on Harmony with Nature is an important milestone toward such a goal.

VALUES

I AM OFTEN ASKED how one scales up successful alternatives. It would be self-defeating, however, to try to either scale up or replicate a DDS or a Parque de la Papa. The essence of this approach is diversity: the recognition that every situation is different. What people can do—and this, indeed, is how successful initiatives spread—is understand the underlying values and apply these in their own communities while networking with like ventures to spread the impact.

The Vikalp Sangam process has identified the following values as crucial: solidarity, dignity, interconnectedness, rights and

responsibilities, diversity, autonomy and freedom, self-reliance and self-determination, simplicity, nonviolence and respect for all life. Around the world both ancient and modern worldviews that are focused on life articulate similar principles. Indigenous peoples and other local communities have lived by worldviews such as *buen vivir*, *swaraj*, *ubuntu* (an African philosophy that sees the well-being of all living things as interconnected) and many other such ethical systems for centuries and are reasserting them. Simultaneously, approaches such as degrowth and ecofeminism have emerged from within industrial societies, seeding powerful countercultures.

At the heart of these worldviews lies a simple principle: that we are all holders of power. That in the exercise of this power, we not only assert our own autonomy and freedom but also are responsible for ensuring the autonomy of others. Such a *swaraj* merges with ecological sustainability to create an *eco-swaraj*, encompassing respect for all life.

Clearly, such fundamental transformations face a deeply entrenched status quo that retaliates violently wherever it perceives a threat. Hundreds of environmental defenders are murdered every year. Another serious challenge is the unfamiliarity many people in the Global North have with ideals of a good life beyond the American dream. Even so, the fact that many progressive initiatives are thriving and new ones are sprouting suggests that a combination of resistance and constructive alternatives does stand a chance.

The COVID pandemic is a catastrophe that presents humankind with a choice. Will we head right back toward some semblance of the old normal, or will we adopt new pathways out of global ecological and social crises? To maximize the likelihood of the latter, we need to go well beyond the Green New Deal approaches in the U.S., Europe, and elsewhere. Their intense focus on the climate crisis and worker rights is valuable, but we also need to challenge unsustainable consumption patterns, glaring inequalities and the need for centralized nation-states.

Truly life-sustaining recoveries would emphasize all the spheres of *eco-swaraj*, arrived at via four pathways. One is the creation or revival of dignified, secure and self-reliant livelihoods for two billion people based on collective governance of natural resources and small-scale production processes such as farming, fisheries, crafts, manufacturing and services. Another is a program for regeneration and conservation of ecosystems, led by Indigenous peoples and local communities. A third is immediate public investments in health, education, transportation, housing, energy and other basic needs, planned and delivered by local democratic governance. Finally, incentives and disincentives to make production and consumption patterns sustainable are crucial. These approaches would integrate sustainability, equality and diversity, giving everyone, especially the most marginalized, a voice. A proposal for a million climate jobs in South Africa is of this nature, as is a feminist recovery plan for Hawaii and several other proposals for social justice in other countries.

None of this will be easy, but I believe it is essential if we are to make peace with Earth and among ourselves. ■

FROM OUR ARCHIVES

Measuring What Matters. Joseph E. Stiglitz; August 2020.

[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)



Christof Koch is chief scientist of MindScope at the Allen Institute in Seattle and of the Tiny Blue Dot Foundation in Santa Monica, as well as author of *The Feeling of Life Itself—Why Consciousness Is Widespread but Can't be Computed*. He serves on *Scientific American's* board of advisers.



NEUROSCIENCE

The Brain Electric

Electrodes that stimulate brain tissue reveal
the topography of conscious experience

By Christof Koch

Illustration by Zara Picken

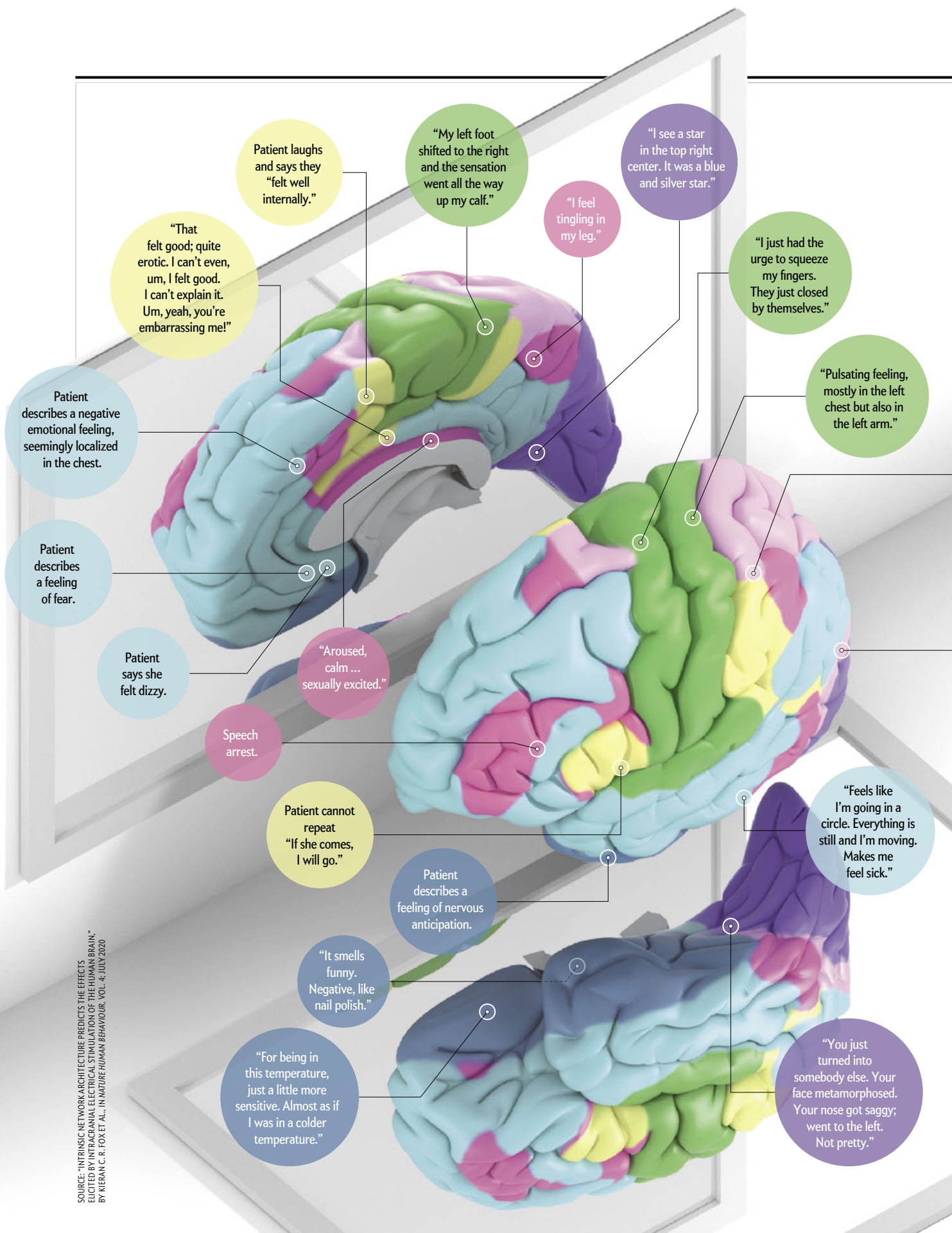
Consider the following experiences:

- You're headed toward a storm that's a couple of miles away, and you've got to get across a hill. You ask yourself: "How am I going to get over that, through that?"
- You see little white dots on a black background, as if looking up at the stars at night.
- You look down at yourself lying in bed from above but see only your legs and lower trunk.

These may seem like idiosyncratic events drawn from the vast universe of perceptions, sensations, memories, thoughts and dreams that make up our daily stream of consciousness. In fact,

each one was evoked by directly stimulating the brain with an electrode. As American poet Walt Whitman intuited in his poem "I Sing the Body Electric," these anecdotes illustrate the intimate relationship between the body and its animating soul. The brain and the conscious mind are as inexorably linked as the two sides of a coin.

Recent clinical studies have uncovered some of the laws and regularities of conscious activity, findings that have occasionally proved to be paradoxical. They show that brain areas involved in conscious perception have little to do with thinking, planning and other higher cognitive functions. Neuroengineers are now working to turn these insights into technologies to replace lost cogni-



Patient laughs and says they "felt well internally."

"My left foot shifted to the right and the sensation went all the way up my calf."

"I see a star in the top right center. It was a blue and silver star."

"That felt good; quite erotic. I can't even, um, I felt good. I can't explain it. Um, yeah, you're embarrassing me!"

"I feel tingling in my leg."

"I just had the urge to squeeze my fingers. They just closed by themselves."

"Pulsating feeling, mostly in the left chest but also in the left arm."

Patient describes a negative emotional feeling, seemingly localized in the chest.

Patient describes a feeling of fear.

Patient says she felt dizzy.

"Aroused, calm ... sexually excited."

Speech arrest.

Patient cannot repeat "If she comes, I will go."

Patient describes a feeling of nervous anticipation.

"Feels like I'm going in a circle. Everything is still and I'm moving. Makes me feel sick."

"It smells funny. Negative, like nail polish."

"For being in this temperature, just a little more sensitive. Almost as if I was in a colder temperature."

"You just turned into somebody else. Your face metamorphosed. Your nose got saggy; went to the left. Not pretty."

SOURCE: "INTRINSIC NETWORK ARCHITECTURE PREDICTS THE EFFECTS ELICITED BY INTRACRANIAL ELECTRICAL STIMULATION OF THE HUMAN BRAIN," BY KIERAN C. R. FOX ET AL., IN NATURE HUMAN BEHAVIOUR, VOL. 4, JULY 2020

Where Experiences Live in the Brain





An atlas published last summer compiled the verbal reports of people with epilepsy whose cortical areas were stimulated with electrodes during surgery. What they felt and perceived varied depending on which brain region was stimulated. All of the 1,537 locations in these 67 patients where current was applied were mapped onto a digital brain model, a simplified version of which is depicted here. When stimulated at these sites, patients talked about their experiences.

“Just really couldn’t move (my fingers) too much; lost the motion. The hand felt a little tight, but the thumb was out of commission.”

“I felt like my arms were moving but they weren’t. I felt side-to-side movements, like floating in the air.”

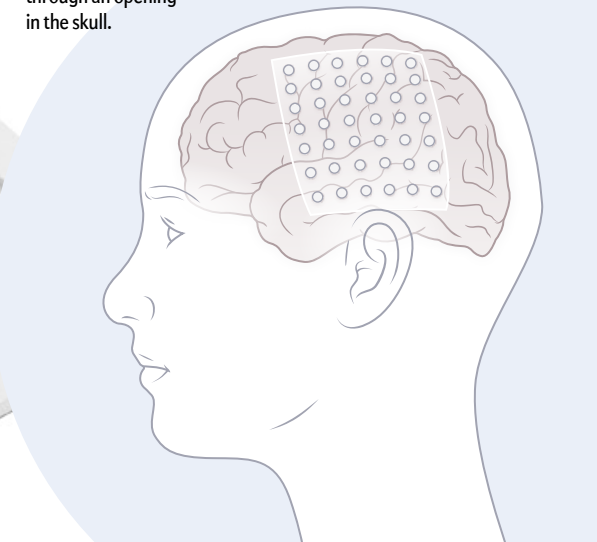
Colors of Cognition

Stimulation was applied to varied brain networks and regions.

-  Somatomotor
-  Visual
-  Dorsal attention
-  Salience
-  Frontoparietal
-  Limbic
-  Default

Points of Stimulation

Researchers placed dozens of electrodes onto the surface of the cerebral cortex accessed through an opening in the skull.



tive function and, in the more distant future, to enhance sensory, cognitive or memory capacities. For example, a recent brain-machine interface provides completely blind people with limited abilities to perceive light. These tools, however, also reveal the difficulties of fully restoring sight or hearing. They underline even more the snags that stand in the way of sci-fi-like enhancements that would enable access to the brain as if it were a computer storage drive.

ANIMAL ELECTRICITY

NERVOUS SYSTEMS operate on the flow of electric currents through ultradense and hyperconnected networks of switching elements. Countless physicians and scientists have worked on this problem over the past two and a half centuries, beginning with Italian physician Luigi Galvani, who in the late 18th century connected a freshly killed frog to a long metal wire. By pointing the wire toward the sky during a thunderstorm, he made the frog’s leg jump and twitch with each flash of lightning. Galvani’s investigations revealed that nerve fibers transmitted “animal electricity,” which is no different in kind from the “atmospheric electricity” that Benjamin Franklin discovered with his kite experiments in Philadelphia in 1752. In 1802 Galvani’s nephew Giovanni Aldini electrically stimulated the exposed brain of a decapitated prisoner during a public event. A jaw quivered. An eye opened. The spectacle may have helped to inspire Mary Shelley to write the classic gothic novel *Frankenstein*.

Subsequent animal studies demonstrated that exciting particular brain regions triggered movements in specific muscles and limbs. These investigations led to the discovery of the motor cortex in the 1870s. In 1874 American physician Robert Bartholow performed the first direct brain stimulation of a conscious patient—a pioneering act clouded in ethical controversy because it caused the patient pain and probably hastened her death. Intracranial electrical stimulation (iES) was refined over the following decades. It became part of the neurosurgeon’s toolbox thanks to the ground-breaking work of Wilder Penfield of the Montreal Neurological Institute, who between the 1930s and the 1950s used iES to map cortical areas that process motor or sensory functions.

In some people with epilepsy, drugs fail to adequately control the number or severity of seizures. Neurosurgery becomes an option if those seizures originate in a delimited neighborhood in the cortex—the outermost layer of the brain involved in perception, motor control, speech, reasoning, and so on—or in closely related structures, such as the hippocampus. Uncontrolled hyperexcitability starts because of local faulty wiring. It can grow and eventually engulf the rest of the brain. How much tissue to remove is a dilemma: cut too little, and seizures may continue; cut too much, and the patient may lose the ability to speak, see or walk. Surgeons must avoid areas of the cortex that are crucial for everyday behavior, such as the primary auditory, visual, somatosensory and motor cortices and the regions controlling understanding and producing speech, areas known as the eloquent cortex.

iES is brought in as a means to look for tissue that needs preserving. Neurosurgeons implant disk-shaped electrodes inside the skull, underneath the tough, leatherlike membrane known as the dura mater. Alternatively, they may insert needlelike electrodes into the brain's gray matter to probe its function. Once the surgeons have identified the focal point of the seizure and removed the electrodes, they extract this tissue in a follow-up operation, and the patient usually becomes seizure-free.

A different use for iES is chronic electrical stimulation, in which the electrodes are left permanently in place. Gentle pulses of current sent through the electrodes can control the tremors and rigidity of Parkinson's disease (a technique called deep-brain stimulation) or reduce the incidence and severity of seizures. Pilot clin-

(no current applied), patients did not feel anything.

Although iES is safe and effective, it is also crude. The low-impedance electrodes are six to 10 square millimeters in area and deliver up to 10 milliamperes of electric current between adjacent electrodes—enough to modulate the excitability of a million or more nerve cells. Still, effects induced by iES can be quite localized. Responsiveness can change from all to none within millimeters or across a sulcus (a groove on the cortical surface).

The Parvizi team found that electrodes in the dedicated sensory and motor areas were far more likely to be responsive than those in areas of the cortex that process higher cognitive functions. Half to two thirds of electrodes above visual and tactile (somatosensory) cortex areas triggered some conscious perception; in regions of the lateral and anteromedial prefrontal cortex, which are involved with higher thought processes, at most one in five electrodes did so. Put differently, electrodes in the back of the cortex—in areas responsible for sensory experiences—were more likely to be active than those toward the front, which consists of regions of the cortex important for cognitive activity such as thinking, planning, moral reasoning, decision-making and intelligence.

Despite their importance for thinking, these regions have little to do with consciousness. Indeed, for the past century neurosurgeons have observed that so long as the eloquent cortex is spared, massive regions of the prefrontal cortex can be ablated without causing obvious deficits in the daily stream of consciousness of these patients. These regions of noneloquent cortex can modulate consciousness, but they are, by and large, not where conscious experience appears to originate. That privilege belongs to more posterior regions—the parietal, temporal and occipital lobes. Why the physical substrate of our mental experiences should be in the back rather than in the front of the brain remains a mystery.

Patients reported electrode-evoked experiences such as seeing distorted faces reminiscent of paintings by Salvador Dalí.

ical experiments are evaluating the use of such implanted electrodes as a visual prosthetic device to enable people with vision impairments to navigate and as a therapy for obsessive-compulsive disorder and depression.

HOT OR NOT

IN JULY 2020 *Nature Human Behaviour* published an atlas highlighting locations across the cortex that, when aroused with electrodes, evoked conscious experiences, such as the storm and the disconnected body mentioned earlier. Led by Josef Parvizi, a professor of neurology at the Stanford University School of Medicine, the clinical team collected data from 67 people with epilepsy. The researchers recorded electrical activity from more than 1,500 sites in the cortex, primarily with subdural electrodes. They mapped the recordings from those sites to spots on a digital brain model so they could compare data from different brains (the pattern of ridges and valleys that give the organ the look of an oversized walnut differs from person to person). The team looked for “responsive” electrodes that triggered some visual or tactile sensation, muscle twitching or disrupted speech. If the patient did not feel anything when stimulated, that electrode was marked as nonresponsive.

Patients reported a range of electrode-evoked subjective experiences: briefly flashing points akin to stars of light; distorted faces like those in the paintings of Salvador Dalí; bodily feelings such as tingling, tickling, burning, pulsing and so-called out-of-body experiences; fear, unease, sexual arousal, merriment; the desire to move a limb; the will to persevere in the face of some great but unrecognized challenge. Mere tickling of neural tissue with a tiny bit of electric current was enough to evoke these feelings. During sham stimulation

TO SEE OR NOT TO SEE

APPLYING iES to the visual cortex triggers optical sensations known as phosphenes, brief flashes that resemble lightning striking a darkened plain. This observation is the source of a long-standing dream of a prosthetic device that restores some vision to people who are blind. Millions worldwide live with deficits in both eyes from retinitis pigmentosa, age-related macular degeneration, glaucoma, infection, cancer or trauma.

Doctors, scientists and engineers started pursuing visual prosthetics in the 1960s but have only recently been able to harness the appropriate technology to help blind people. One prominent example is a device known as Orion, developed by Second Sight Medical Products in Los Angeles. A tiny camera, mounted on glasses, converts images into pulses and transmits them wirelessly to fire 60 electrodes sitting on the visual cortex. The handful of people who have had this experimental device implanted into their brain perceive clouds of dots that allow them to navigate. “It’s still a blast every time I turn it on,” one study participant reports. “After seeing nothing to all of

a sudden seeing little flickers of light move around and figuring out that they mean something. It's just amazing to have some form of functional vision again." Orion significantly improves the quality of life for people who previously lived in complete darkness. It enables them to safely cross the street or locate a doorway. But it does not allow them to regain the ability to recognize figures, shapes or letters.

A team at the University of California, Los Angeles, and the Baylor College of Medicine led by neurosurgeon Daniel Yoshor recently did accomplish this feat, as described in the journal *Cell*. They stimulated nearby locations in the visual cortex to trigger phosphenes that appear close together, demonstrating that the external visual environment is mapped in a regular fashion onto the surface of the visual cortex. This observation has led to the erroneous belief that individual phosphenes are like pixels on a computer display—that is, if you were to simultaneously stimulate a series of points on the cortical surface in the shape of a cross, the subject should see points forming a cross. This does not happen, however.

Stimulating more than one location yields unpredictable results. In one participant, simultaneous stimulation of five electrodes, each one associated with one discrete phosphene, triggered the illumination of two large phosphenes that did not coalesce into a letter or any other coherent form. If the researcher staggered activation of the electrodes in time, however, the subject could identify shapes. The staggering reflected the delay required to trace the shape of a letter, as if the researcher were outlining a letter into the hand of the subject or onto a piece of paper. In this more dynamic manner, the subject with the implant whose vision was blocked could identify a stimulus by tracing out a Z, N, V and W, rapidly distinguishing upward from downward motion or discriminating sequences of letters.

Seeing the shape of a single letter is not quite the same as seeing a glorious sunset over Homer's wine-dark sea, but it represents progress. Why staggering stimulation in time improves perception is not clear and reveals our ignorance concerning functioning cortical circuits.

WHAT LIES AHEAD

TECHNOLOGICAL PROGRESS in so-called brain-machine interfaces is proceeding at a rapid pace. Elon Musk's company Neuralink released in April of this year an impressive video showcasing a monkey playing the computer game Pong without any controller. This was achieved with two small chips implanted into the left and right motor cortices of the animal. Each chip has 1,024 hair-like electrodes that record the chattering of individual neurons. Collectively they convey the monkey's intention to quickly move the paddle up or down the screen to return the ball to the opposite side. Everything was done wirelessly; no electronics or dangling wires were protruding from the monkey's head. Many assume that surgeons will soon routinely replace or bypass faulty biological components—defective eyes or ears, failing memories—with superior electronic substitutes. Such optimism ne-

glects the fact that all of this requires trepanation of the skull. In general, turning scientific insights into actual therapeutics is done in decades rather than in years. I am pretty confident that such enhancements will not occur in my lifetime (I'm now 64).

The "easiest" hurdles to overcome on the way to such a utopian (or perhaps dystopian) future are technological ones—reliably, quickly, and delicately reading and writing the brain electric. Neuralink's device represents the best of currently available technology and will certainly improve in future iterations. But we still have a long way to go before we can identify which of the 50,000 or more neurons in any quinoa-sized bit of brain matter are involved in any given perception or action. Only when that happens will it be possible to limit electrical stimulation to just those neurons and not the output cables of nearby cells. That Parvizi and his colleagues failed to elicit conscious perceptions in more than half of all stimulated sites shows we lack tools capable of reliably eliciting *any* sensations through electrical stimulation, let alone being able to evoke any highly specific one.

Even more challenging are surgical and regulatory hurdles that demand that prosthetic devices can be routinely and safely implanted by drilling through the hard skull into the gray matter underneath while minimizing the risk of infections, bleeding and seizures. Furthermore, the electronics has to function for years inside warm, wet and salty biological tissue—hardly an optimal operating regime. You don't want your prosthetic device to corrode or freeze up in the equivalent of the blue screen of death. For this reason, neural implants will remain a matter of last resort for those with severe sensory or motor impairments. As neuroprosthetic devices move through clinical trials, they will help people with visual impairments see and those with physical disabilities perform actions such as steering a wheelchair with their thoughts, like the mind-Pong-playing monkey. For everyone else, the benefits of highly invasive brain surgery are unlikely to outweigh the costs.

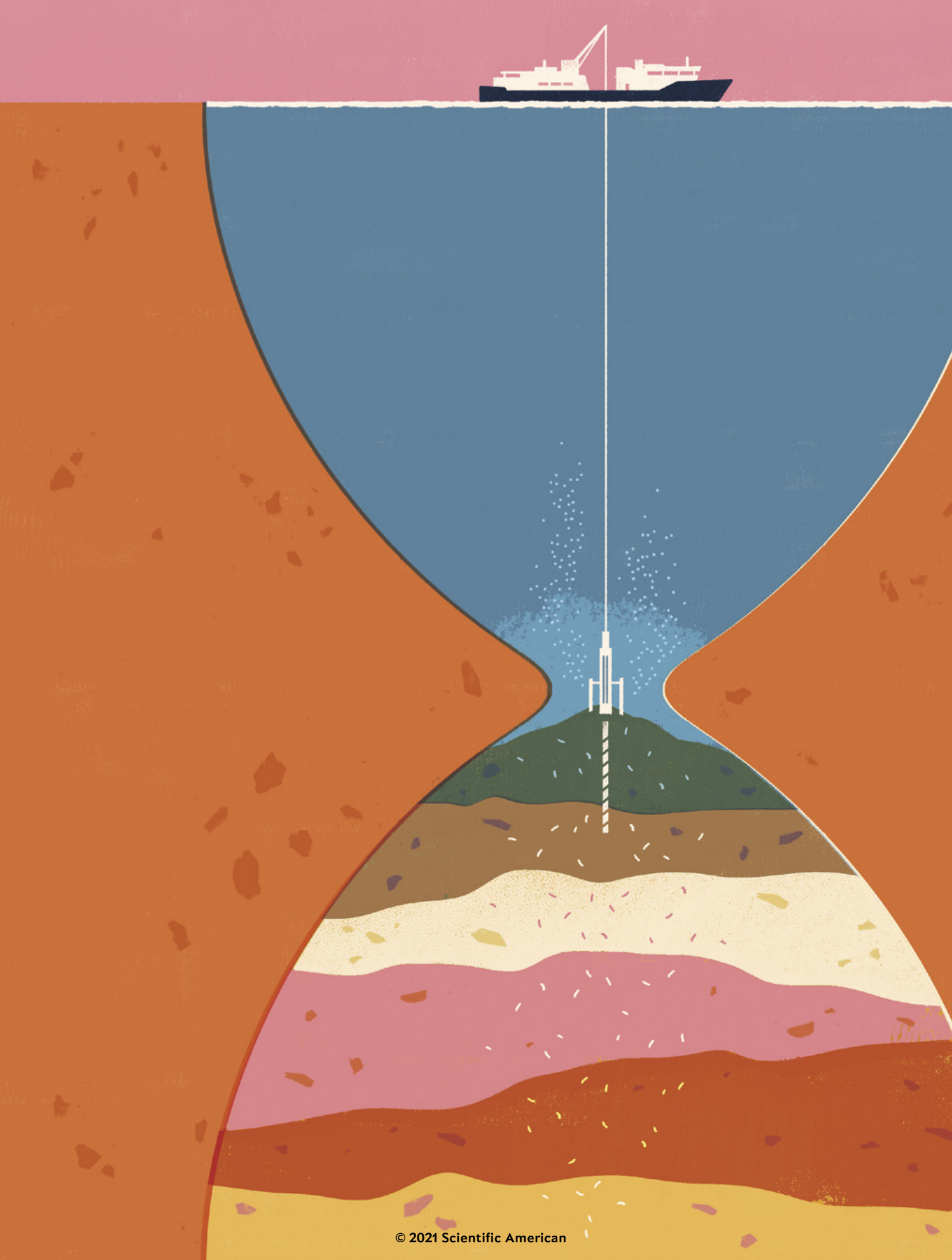
But the true Annapurna ahead involves understanding how three pounds of excitable brain matter is responsible for seeing, moving and suffering. Yes, the physical substrate of heaven and hell is rooted in bioelectric signals that obey natural laws. But that tells us precious little about how a trillion electrical signals spiking each second, streaming over networks of tens of billions of heterogeneous cells, constitute a sight, sound or emotion.

Intracranial brain stimulation highlights the daily miracle of the brain's water changing into the wine of consciousness. The question remains, though: What is it about the brain, the most complex piece of active matter in the known universe, that turns the activity of 86 billion neurons into the feeling of life itself? ■

FROM OUR ARCHIVES

Awakening an Unconscious Mind. William Skaggs; Scientific American Mind, July 2014.

[scientificamerican.com/magazine/sa](https://www.scientificamerican.com/magazine/sa)



MICROBIAL SCIENCE

REAL LIVING FOSSILS

After 100 million years
trapped in ocean sediment,
microbes woke up and multiplied

By Jennifer Frazer

Illustration by Chris Gash

Jennifer Frazer, an AAAS Science Journalism Award-winning science writer, authored *The Artful Amoeba* blog for *Scientific American*. She has degrees in biology, plant pathology and science writing.



IN 2010 SCIENTISTS FROM THE INTEGRATED OCEAN DRILLING PROGRAM (IODP) SAILED INTO the South Pacific Gyre, a marine desert more barren than all but the most arid places on Earth. Near the center of the gyre is the Oceanic Pole of Inaccessibility—best known by fans of H. P. Lovecraft as the home of the be-tentacled Cthulhu—as well as the South Pacific garbage patch, where microplastic particles accumulate. At times the closest people are astronauts passing above on the International Space Station.

Although ocean currents swirl around it, within the gyre the water stills. Few nutrients enter, and life struggles. Here it takes at least one million years for a meter of marine “snow”—the corpses, poo and dust that transfer energy from the light-rich upper layers to the depths—to pile up on the bottom. It is the least productive patch of water on the planet.

Through this seawater, the IODP team lowered kilometers of pipe from a derrick more than 60 meters high. Twelve thrusters held the entire rig just so in the heaving seas. Once the pipe hit bottom, a drill plunged down to 75 meters into pelagic clay and calcareous nannofossil ooze at multiple different sites.

By the time the cores of sediment were raised to the surface, the tubes contained up to 100 million years of Earth history. What the team wanted to know was how long and in what state microbes trapped in this milieu could survive in an almost completely empty oceanic refrigerator. As expected, the sediment samples did not contain many bacterial cells to begin with: just 100 to 3,000 per cubic centimeter, which is 10 to 10 million times less than at equivalent depths in more productive waters.

But when the scientists fed those cells in the laboratory, something unexpected occurred. One hundred million years of starvation might have made the cells microbial “zombies”—alive but incapable of growth or able to grow but not at a rate humans could measure. In the early 2000s a few bacteria isolated from marine sediments up to 35 million years old were coaxed to grow in culture, but the experiment was not designed to gauge their growth. A 2017 study of oxygen-free coal-bed microbes (which were deposited on land 12 million to 16 million years ago but lat-

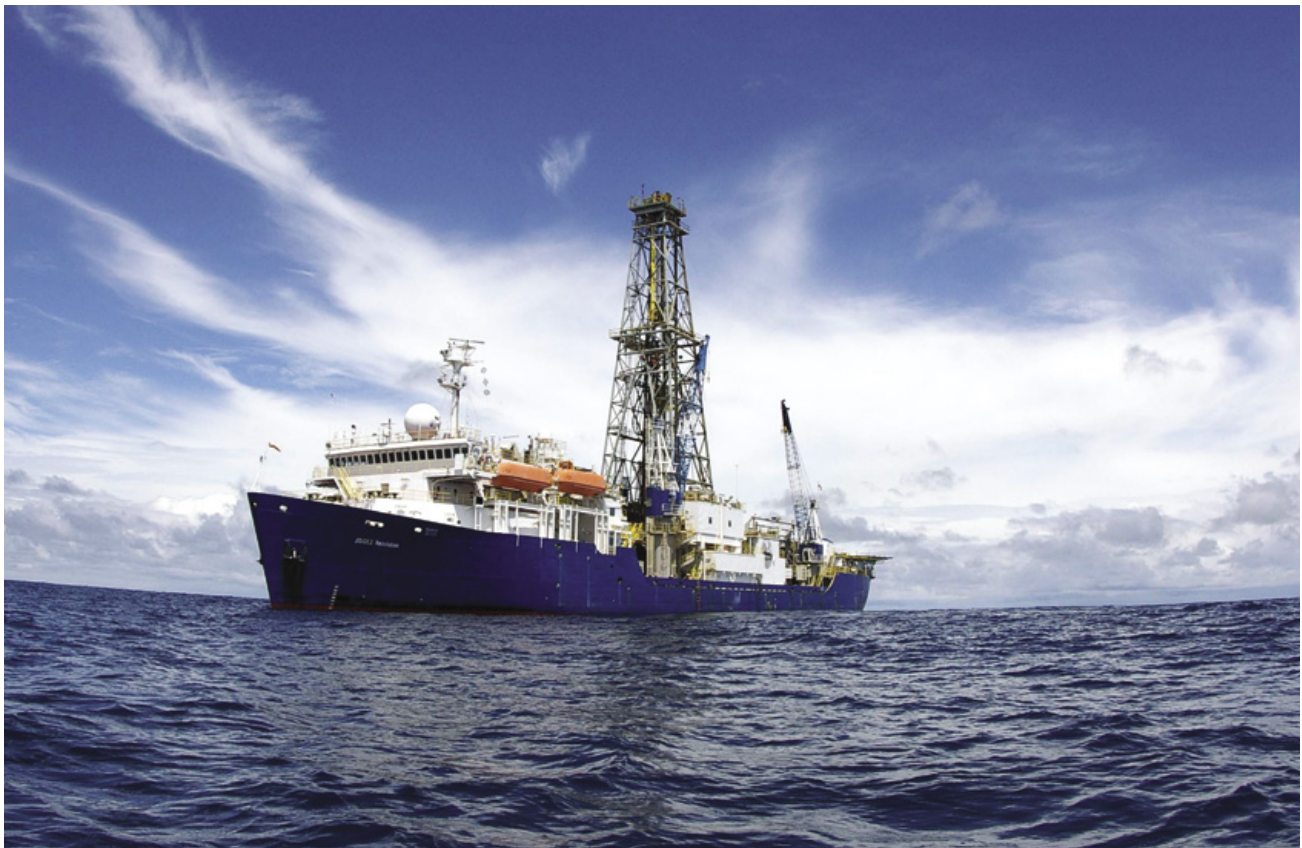
er submerged by ocean) found that the resurrected subjects did grow, only extremely slowly. Their doubling times were on the order of months to a century, some of the slowest ever directly measured.

But in this study, which was published in July 2020 in *Nature Communications*, up to 99 percent of the microbes that were fed quickly “woke up,” ate and got to work doing what bacteria do. Within 68 days of incubation they had increased their numbers up to 10,000-fold, doubling about every five days. Their progeny contained specially labeled isotopes of carbon and nitrogen that could have been obtained only by eating the food the scientists offered.

It is worth pausing to consider the meaning of these results. Seventy percent of Earth’s surface is covered by marine sediment, whose microbial residents represent up to half of all microbial biomass on the planet. In this experiment, cells that may have settled to the bottom of the ocean when plesiosaurs swam overhead awoke and multiplied. Four geologic periods had ground by, but these microbes, protected from cosmic rays by a thick coat of ocean and sediment, persisted. When dredged up and offered a bite, they carried on as if nothing unusual had happened.

In a sense, it hadn’t. If it feels like forever since the pandemic began, imagine being starved in the dark for 100 million years. The dense sediment, which approaches something like flourless chocolate cake, has an estimated pore size of 0.02 micron. Given that a typical bacterium is a few microns across, you can see the challenges inherent to migrating in search of food or even hoping some blunders into you.

Some bacteria, many of which are anaerobic, make structures called endospores that are fortified



and metabolically inactive, seemingly to allow bacteria to endure harsh conditions. Spores have often been suggested as a vehicle for superannuated bacteria. Yet when the scientists identified the gyre-sediment cells by probing their DNA, they saw that spore-forming types were relatively absent. The majority of the revived bacteria, it turned out, breathed oxygen.

An even more surprising find was a thriving population of light-harvesting bacteria discovered in one sample 557 days into its incubation. Called *Chroococcidiopsis*, this cyanobacterium has a reputation for survival so formidable it is being considered for terraforming Mars. In addition to being able to live under translucent rocks in dry, cold, salty and radiation-drenched places, it has the unusual ability to capitalize on red light. How this photosynthetic microbe managed to reproduce in a dark lab chamber remains a mystery.

To be sure, although the sediment in which the cells were trapped was up to 100 million years old, the age of individual cells remains uncertain. Some are possibly descendants of the original community and therefore much younger. But reproduction is costly, and given the conditions, it seems likely to be rare. Putting it all together—the tight quarters, the lack of spores and the rapid reanimation—the authors of the *Nature Communications* paper think that the microbes in this impoverished sediment have been alive but idling the entire time.

Scientists have flirted with the idea that individual bacteria may survive without reproducing for many millions of years. (That will remain unknown until we develop techniques that can date microbes, not just sediment.) A few years ago, when I wrote about bacteria that were resurrected from Paleozoic coal for my *Scientific American* blog, I speculated that under certain highly constrained but possibly abundant conditions, bacteria may be effectively immortal. Time does appear to take a toll: the oldest cells from the Cretaceous seafloor sediment multiplied about half as fast as their more spry brethren that had been down there “only” a few million years. Still, mounting evidence suggests that we may be sitting atop a planet that is full of living fossils that are literally that—both fossils and alive.

The people who love dinosaurs (and to be fair, who among us aren’t dinosaur people?) have their museums filled with bones and teeth and tracks. The plant people have their petrified forests and fossil fronds. But the microbe people have something even better: our dinosaurs aren’t dead. ■

SEAFLOOR-DRILLING SHIP, the *JOIDES Resolution*, collected sediment from deep below the South Pacific Gyre.

FROM OUR ARCHIVES

Foiling a Faint Sun, Sarah Simpson; April 2003.

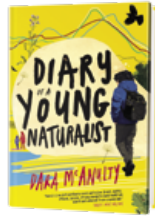
scientificamerican.com/magazine/sa

Finding Hope in Nature

A teenager with autism is moved to protect the planet

In this lyrical and often dazzling memoir, 17-year-old Dara McAnulty brings readers into close communion with the natural world while offering an intimate look at what it's like to live with autism. *Diary of a Young Naturalist* is structured like a journal and spans one year, during which McAnulty's family moves cross-country from their home in Northern Ireland's County Fermanagh to the mountainous County Down. The move is at first difficult for the teen, who feels most comfortable in familiar places. But as he explores his new home's wooded surroundings, his passion for naturalism deepens.

The author's autism is tightly entwined with his writing and fascination with nature. "My head is pretty hectic most of the time," he writes, "and watching daphnia, beetles, pond skaters and dragonfly nymphs is a medicine for this overactive brain." Inspired by his father, a conservationist, McAnulty finds specimens to admire on family trips through the woods or along a stream. He contrasts these outdoor adventures with time spent in a classroom, a space he calls "flat and uninspiring." In nature, he's left unbothered by the



Diary of a Young Naturalist

by Dara McAnulty. Milkweed Editions, 2021 (\$25)

The natural beauty of McAnulty's new home in County Down inspired his observations.

need to concentrate on the words and facial expressions of others, abilities that do not come easy for him.

The exuberance he feels while examining plants and animals is palpable—he admits he doesn't "have a joy filter." But all that emotion is balanced with careful observations. The parts of a beetle's body, for example, are identified by their scientific names, plants by their Latin ones.

The book's most powerful moments involve encounters with environmental destruction caused by humans—a seal injured by plastic, a bird's egg destroyed by a lawn mower. Witnessing such damage sparks a "solar flare of anger" within the author, which, we learn, he is using to help light a movement for climate advocacy. An admirer of Greta Thunberg, McAnulty writes about the terror he feels when participating in climate marches attended by large numbers of people. But passion overcomes his fear. In addition to marching, he gives public speeches and films documentaries with English naturalist Chris Packham. Voices like his—and books like this one—empower us to appreciate and protect our planet. —Amy Brady

Double Blind

by Edward St. Aubyn. Farrar, Straus and Giroux, 2021 (\$27)



Best known for his darkly comic novels about an English aristocrat named Patrick Melrose, Edward St.

Aubyn returns with a rollicking tale of love and science in a world increasingly hostile toward both. *Double Blind*'s hectic—but very funny—plot stars two Oxford graduates, Lucy and Olivia, who fall in love, respectively, with a virtual-reality entrepreneur funding brain research and a botanist dead set on discrediting neuroscience. St. Aubyn's distinctive waggishness is on display throughout, punctuated with scientific verbiage ("mycorrhizal network") and quotes from Wittgenstein. —A.B.

Islands of Abandonment: Nature Rebounding in the Post-Human Landscape

by Cal Flynn. Viking, 2021 (\$27)

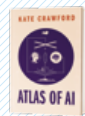


Cal Flynn, a Scottish journalist, tours degraded landscapes on three continents—abandoned farm-

land, industrial ruins, radioactive forests—and finds strange beauty in the "feral ecosystems" that reclaim even the most toxic terrain. Through deep research and graceful writing, she shows that this "corrupted world" has "a great capacity for repair, for recovery... if we can only learn to let it do so." —Seth Fletcher

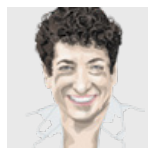
Atlas of AI

by Kate Crawford. Yale University Press, 2021 (\$28)



In this cartographic approach to defining AI, scholar and *Scientific American* advisory board member Kate Crawford deftly argues that it is "neither artificial nor intelligent" but rather "fundamentally political." The lens through which AI has long been described—as a neutral technology destined for dominance—is an intentionally abstract narrative that comes from existing architectures of power. Crawford views AI as an extractive industry that mines not just data but lithium, labor and fossil fuels, while often perpetuating systems of injustice. —Jen Schwartz





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).

Do Republicans Mistrust Science?

GOP leaders have been casting doubt on evidence for decades

By Naomi Oreskes

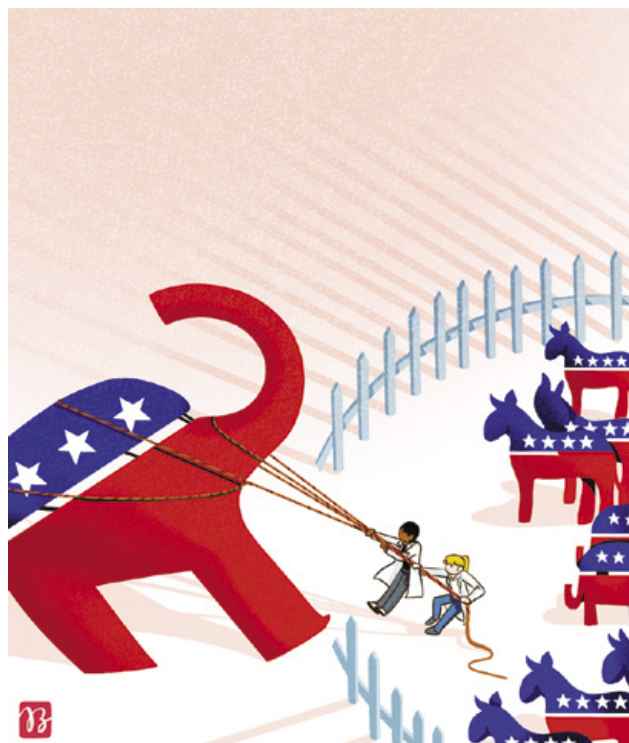
This past winter several polls asked respondents whether they would get a COVID-19 vaccine when one became available to them. Nearly half of Americans—47 percent by one count—said “no” or “maybe.” Vaccine hesitancy has been decreasing in recent months as evidence of vaccine safety has accumulated, but this number indicates a potentially major challenge to achieving herd immunity and returning life in this country to normal. Even more troubling is that U.S. vaccine hesitancy is not evenly distributed.

At the start of the vaccine rollout, there was a lot of talk about vaccine hesitancy among Black and Hispanic populations, but recent data suggest the problem was one more of access than of reticence. A CBS news poll in March, for example, found that vaccine hesitancy among these groups was no more prevalent than among white populations. But such hesitancy is disproportionately high among Republicans.

A different CBS news poll in January found that only 28 percent of Republicans planned to get a vaccine as soon as possible, and a whopping 71 percent said they would either “wait to see what happens to others” (42 percent) or never get one (29 percent). In contrast, 54 percent of Democrats and 38 percent of Independents planned to get the vaccine right away. In February a [Monmouth University poll](#) yielded a similarly worrisome result: 42 percent of Republicans said they would avoid ever getting the vaccine. In March the number was still at 33 percent. Moncef Slaoui, head of Operation Warp Speed under Donald Trump, said he was very concerned that people were knowingly putting themselves in harm’s way and asked Trump and other Republicans to speak up to encourage vaccination.

Would that help? It’s not clear. Among Americans in general, the top two reasons for vaccine hesitancy around that time were concerns that vaccines were still too untested (58 percent) and that there was a risk of side effects (47 percent). For these people, facts about vaccine safety may help allay their objections. Republican hesitancy, however, seems to have different and deeper roots.

In March longtime Republican pollster Frank Luntz led a focus group with Trump voters. Many of them stressed that they were not “anti-vaxxers” who opposed all vaccines. Nor were they “COVID deniers.” They acknowledged that the disease was real; many had family and friends who had had it, and some had been ill themselves. But they were suspicious of the federal government and had a sense that science was often oversold. CBS found similar results, reporting that 60 percent of respondents say “scientists have been wrong on the coronavirus most or all of the time” and that mask mandates and social distancing requirements do not



help control the spread of the virus. And most of these people are Republicans. Luntz concluded the best approach would *not* be for Republican leaders to tout the vaccine but for apolitical messengers—a person’s own doctor, say, or spouse—to offer facts in an honest, nonpartisan way.

Fair enough, but why do so many Republicans distrust government, including government science, and think scientists are “always getting it wrong”? A large part of the answer is that this is what the party’s spokespeople have been saying for 40 years, from the early days of acid rain to our ongoing debates about climate change. It was Luntz himself who, more than 20 years ago, designed the [Republican party’s strategy](#) to fight climate change by insisting there was no scientific consensus on the issue. It has mostly been Republican governors resisting mask mandates, even when science showed they slowed the spread of COVID-19. And it was, by and large, Republican governors lifting those mandates in the spring, even while Rochelle Walensky, director of the Centers for Disease Control and Prevention, begged them not to.

Everyone deserves accurate information to be presented in an apolitical way and to be addressed with respect and not condescension. But the reality is that most of the science that matters most comes from the government or from scientists funded by the government. Until Republican leaders stop telling voters not to trust the government, many of them won’t trust science. **SA**

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JUNE

1971 Social Strata of Turkeys

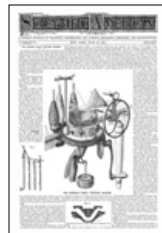
“We made a detailed study of a population of wild turkeys living in and around the Welder Wildlife Refuge in Texas and found an astonishing degree of social stratification, greater than had previously been seen in any society of vertebrates short of man. The status of each individual in this turkey society is determined during the first year of life, and it usually remains fixed for the animal’s lifetime. One of the consequences is that most of the males never have an opportunity to mate. Presumably this phenomenon carries some benefits for the society, which presents an interesting subject for speculation. Perhaps the Welder turkeys offer a moral for human conduct, suggesting that people might often benefit, even as individuals, by giving less attention to self-gratification and more to group effectiveness.”



1971



1921



1871

sions on the lunar surface are the result of volcanic action. But more recently a rival hypothesis has arisen: the crater-like formations are the result of the impact and penetration of meteoric bodies. The evidence is the result of military experiments carried out on Langley Field [in Virginia]. The effort was directed at the purpose of getting definite information on the effect of dropping bombs from airplanes. Photographs disclose bomb-formed depressions markedly like those found on the moon.”

1871 Turtles Chew Telegraph

“A recent announcement of the Superintendent of the International Telegraph Company between Punta Rosa and Key West has placed a new item upon the list of dangers to which ocean cables may be subjected. The cable in question had, during the past year, been so frequently

injured or broken, that a careful examination [showed] that the damage was to be ascribed to the loggerhead turtles, which are abundant in those waters. In many places, the cable presented the appearance of having been bitten through; and in others of having been crushed from both sides until it had become so much flattened as to destroy its conductivity. Where the breaks and injuries occur, there the loggerheads most abound. The company has sent an order for a much larger and stronger cable, and when it is laid, the assailants will have something more substantial than the present steel-wound cable upon which to whet their teeth.”

Young Ageism

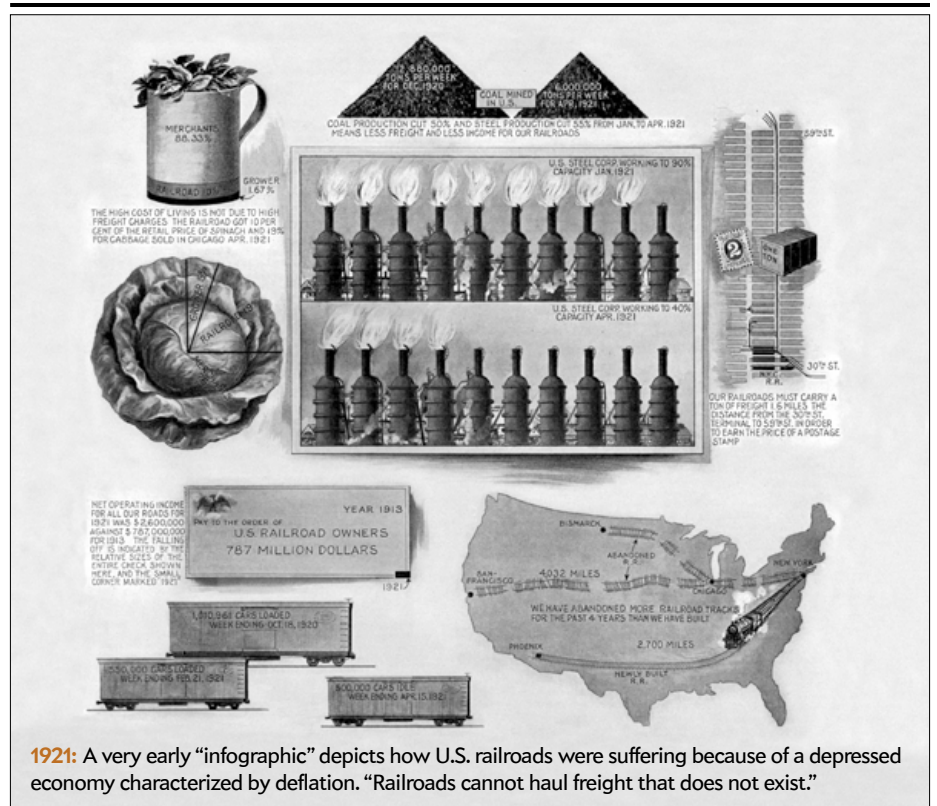
“The number of men whose minds are weaker at forty or fifty is legion. Their minds are in a feeble, emaciated condition, unable to cope with the great questions of the day.”

1921 Lightning Strikes Twice

“The timeworn theory that lightning never strikes twice in the same place has been modified by forest experts of the U.S. Department of Agriculture to this extent: Lightning very often strikes in nearly the same places. It has its zones where its appearance may usually be counted on with each electrical storm. With the accumulation of data on causes and locations of fires in the national forest, these lightning zones could be mapped out and protective measures introduced—such as fire lines, regulated grazing and cleaning out of dead trees—which would more or less automatically control lightning fires at the start, the foresters believe.”

Moon Bombs

“Markings on the moon’s surface are plainly visible to the naked eye. It has been held that depres-

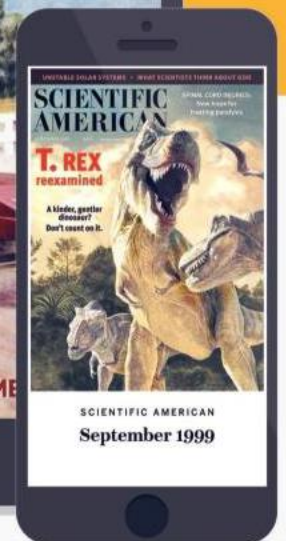


1921: A very early “infographic” depicts how U.S. railroads were suffering because of a depressed economy characterized by deflation. “Railroads cannot haul freight that does not exist.”

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Text and Graphic by Katie Peek

Crewed Space Launches (1961–2020)

By the end of 2020 humans had crossed into space—a boundary defined here as 80 kilometers above sea level—on 343 different voyages. They appear here on a time line, each as a distinct arc colored by vessel type. Any flight that carried crew across that 80-km line is included—space planes and lunar landers alike.

Arc direction indicates space agency type

- Private enterprises Right-leaning arc
- Government programs Left-leaning arc

Color denotes vessel class

Arc height marks mission destination

- Deep space 2,000 km+
- Low-Earth orbit 250–2,000 km
- Suborbital 80–250 km

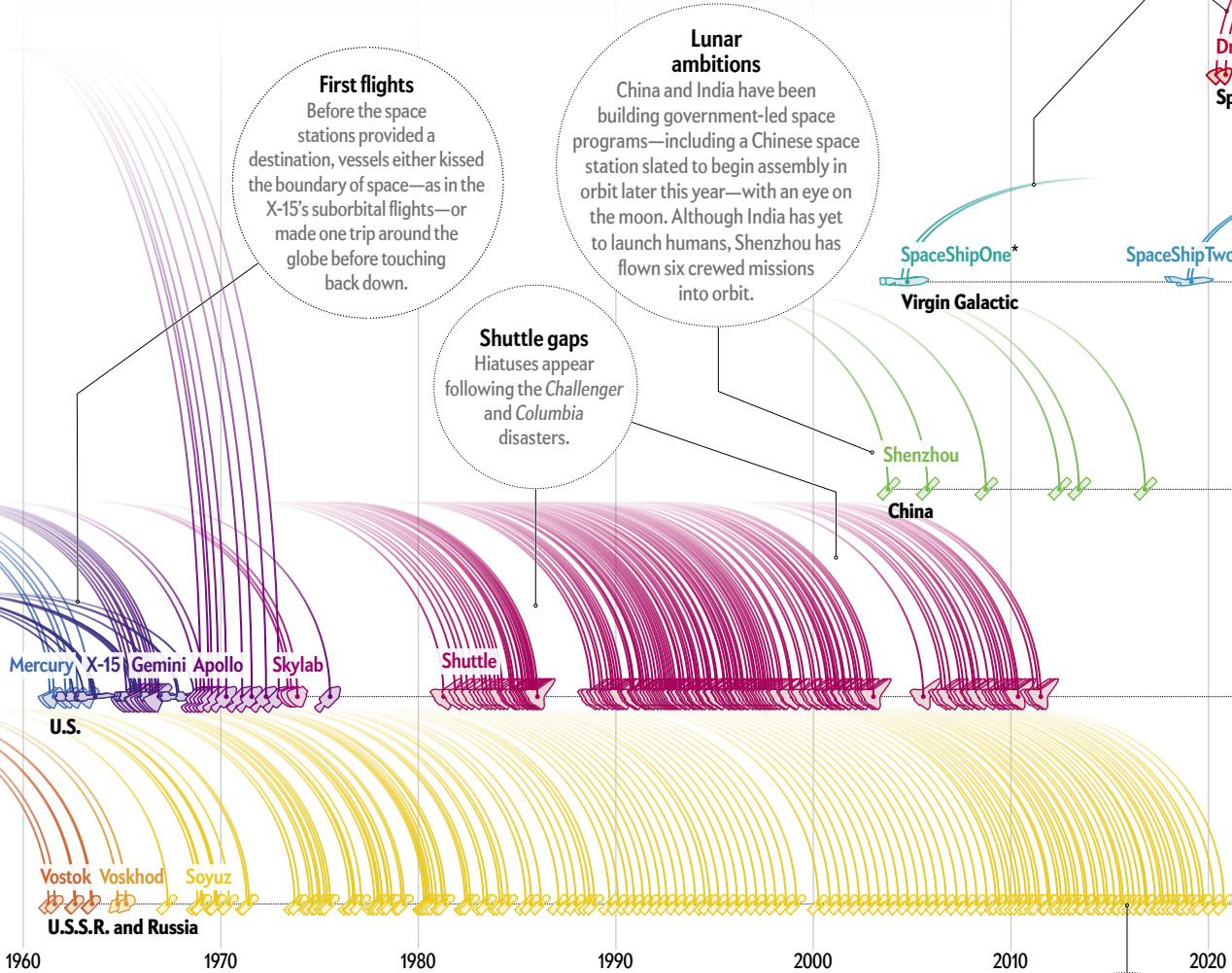
Private practice
Virgin Galactic space planes flew across the boundary to space in the early 2000s. Today SpaceX and Boeing are developing programs that will carry astronauts and tourists to orbit.

First flights
Before the space stations provided a destination, vessels either kissed the boundary of space—as in the X-15's suborbital flights—or made one trip around the globe before touching back down.

Lunar ambitions
China and India have been building government-led space programs—including a Chinese space station slated to begin assembly in orbit later this year—with an eye on the moon. Although India has yet to launch humans, Shenzhou has flown six crewed missions into orbit.

Shuttle gaps
Hiatuses appear following the Challenger and Columbia disasters.

Soyuz, workhorse
The Russian standby has carried humans to orbit 143 times—representing 40 percent of all crewed launches—since its first flight in 1967. Design upgrades have kept Soyuz vessels safe and efficient, although they remain single-use capsules.



The New Final Frontier

Human spaceflight diversifies

We are entering a new era in sending people beyond Earth. After the Apollo moon program, U.S. space shuttles and Russian Soyuz flights were the only game in town. Those ferries carried astronauts to and from low-Earth orbit, where space stations Skylab, Mir and the ISS hung around the planet. Today there is far more diversity among launchers and destinations, says astronomer Jonathan C. McDowell of the Harvard-Smithsonian Center for Astrophysics. SpaceX, Boeing and other private companies are getting off the ground and plan both astronaut flights and space tourism. Deep-space travel is again on NASA's horizon. "For a long time, U.S. human spaceflight was in postshuttle doldrums," McDowell says. "That's definitely over now."

*SpaceShipOne was made by Scaled Composites, which was later acquired by Virgin Galactic.

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